THE LIMNOLOGY OF LAKE CLARK, ALASKA

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THE LIMNOLOGY OF LAKE CLARK, ALASKA

A

THESIS

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By

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ABSTRACT

This study gathered baseline limnological data to investigate the thermal structure, water quality, phytoplankton, and zooplankton of Lake Clark, Alaska. Results indicate Lake Clark is oligotrophic and mixes biannually, but stratification is weak and thermoclines are deep. Longitudinal gradients were seen in measurements of temperature, suspended solids, turbidity, light penetration, algal biomass, and zooplankton density. Wind and tributary inputs determine the thermal regime. Glacially-influenced tributaries drive turbidity and light gradients by introducing suspended solids to the inlet end of the lake. Suspended solids likely create the algal biomass gradient by limiting the light available for photosynthesis in the inlet basin. Algal biomass and turbidity gradients may interact to create an area of high productivity and low predation risk, causing high zooplankton concentrations in the central basin. Oxygen supersaturation was discovered in the hypolimnion but remains unexplained. Because tributaries are glacially influenced, Lake Clark could be sensitive to global warming.

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INTRODUCTION

The impetus for studying the limnology of Lake Clark comes from a combination of national policy and the lack of adequate scientific studies on this lake and other glacially turbid lakes. Lake Clark National Park and Preserve was created in 1980 under the Alaska National Interest Lands Conservation Act (1980) and was established in part to "...protect the watershed necessary for the perpetuation of the sockeye salmon in Bristol Bay...maintain the scenic beauty and quality of portions of the Alaska Range and Aleutian Range, including active volcanoes, glaciers, wild rivers, lakes, waterfalls, and alpine meadows in the natural state." Furthermore, it is NPS policy to "define, assemble, and synthesize comprehensive baseline inventory data describing the natural resources under its stewardship, and identify the processes that influence those resources" (NPS, 2001).

Previous information on the limnology of Lake Clark is limited. Some limnological data are provided by Donaldson (1967), Burgner et al. (1969), Mathisen and Poe (1969), Dale and Stottlemyer (1986), Stottlemyer and Chamberlain (1987), and Chamberlain (1989). Schlenger (1996) collected some lake measurements and zooplankton, Deschu (2000) collected surface water quality and nutrient data, and Brabets (2002) studied Lake Clark's major inflows.

High latitude glacial lakes have not been well studied, although useful information on their limnology has been provided by Lloyd et al. (1987), Koenings et al. (1990), Sweetman (2001), and Edmundson and Mazumder (2002). Lake Clark is unusual even among glacial lakes because it exhibits a strong longitudinal turbidity gradient and is remarkably long and deep. These characteristics make Lake Clark a microcosm for studying the interrelations of temperature, turbidity, light, phytoplankton, and zooplankton.

In an effort to fill these knowledge gaps, and provide data for NPS management, this project focused on the elements of limnology in Lake Clark that affect the growth and distribution of juvenile sockeye salmon (*Oncorhynchus nerka* (Walbaum)). The objectives of the project were to study the spatial and temporal variations in temperature, dissolved oxygen, pH, conductivity, light, turbidity, suspended sediments, color, nutrients, algal biomass, and zooplankton abundance, distribution, biomass, taxonomic composition, and length-frequency.

Study Area

Lake Clark is centered at about 60°15'N, 154°15'W. It fills a deep, elongated, glacially derived trough that follows a major fault line (Figure 1). It is the sixth largest lake in Alaska and one of the largest lakes in the United States. The lake is composed of three major basins, the northern two of which are not distinctly separated. The lake is subjected to a subarctic inland climate (Weeks, 2001; Western Regional Climate Center/RAWS).

Thirteen watersheds contribute to Lake Clark, but the six largest, which account for the bulk of inflow, empty into the two northern basins of the lake (Figure 2). These tributaries are diverse in their input characteristics and range from glacial to bog-fed in nature (Table 1).

To the north and west of Lake Clark lie the Chigmit Mountains. To the west and south, the mountains give way to tundra plains dotted with bogs, wetlands, and small ponds. The Lake Clark basin follows the Castle Mountain/Lake Clark Fault, a major fault line of the Alaska Peninsula. The bedrock geology of the Lake Clark watershed is no more than 225 million years old (Weeks, 2001). Of the six major watersheds to Lake Clark, three (2,477 km^2) have bedrock geology dominated by Cenozoic intrusive formations, and three (4,305 km^2) are dominated by Mesozoic sedimentary rocks (Brabets, 2002). Soils in the low-lying areas of the Lake Clark watershed are primarily andisols, histosols, and spodosols, but the remainder of the Lake Clark basin is dominated by mountainous terrain with virtually no soils (Brabets, 2002). Annual precipitation in the Lake Clark drainage ranges from 600 mm in the low-lying western areas to 2,000 mm in the mountainous eastern regions (Jones & Fahl, 1994).

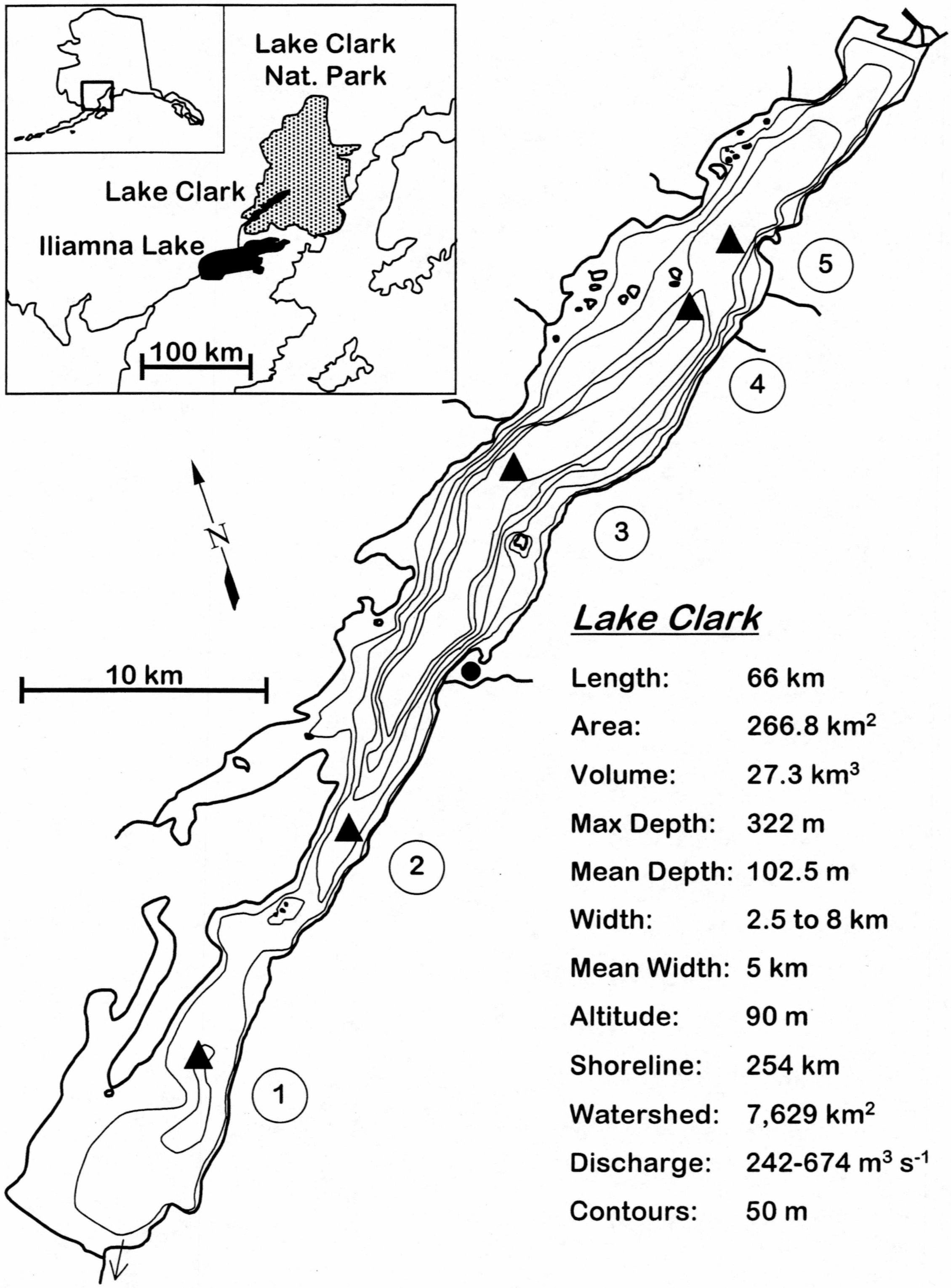

Figure 1. Morphometry and location of Lake Clark, showing sampling stations (redrawn from Anderson 1969). (● = Port Alsworth.)

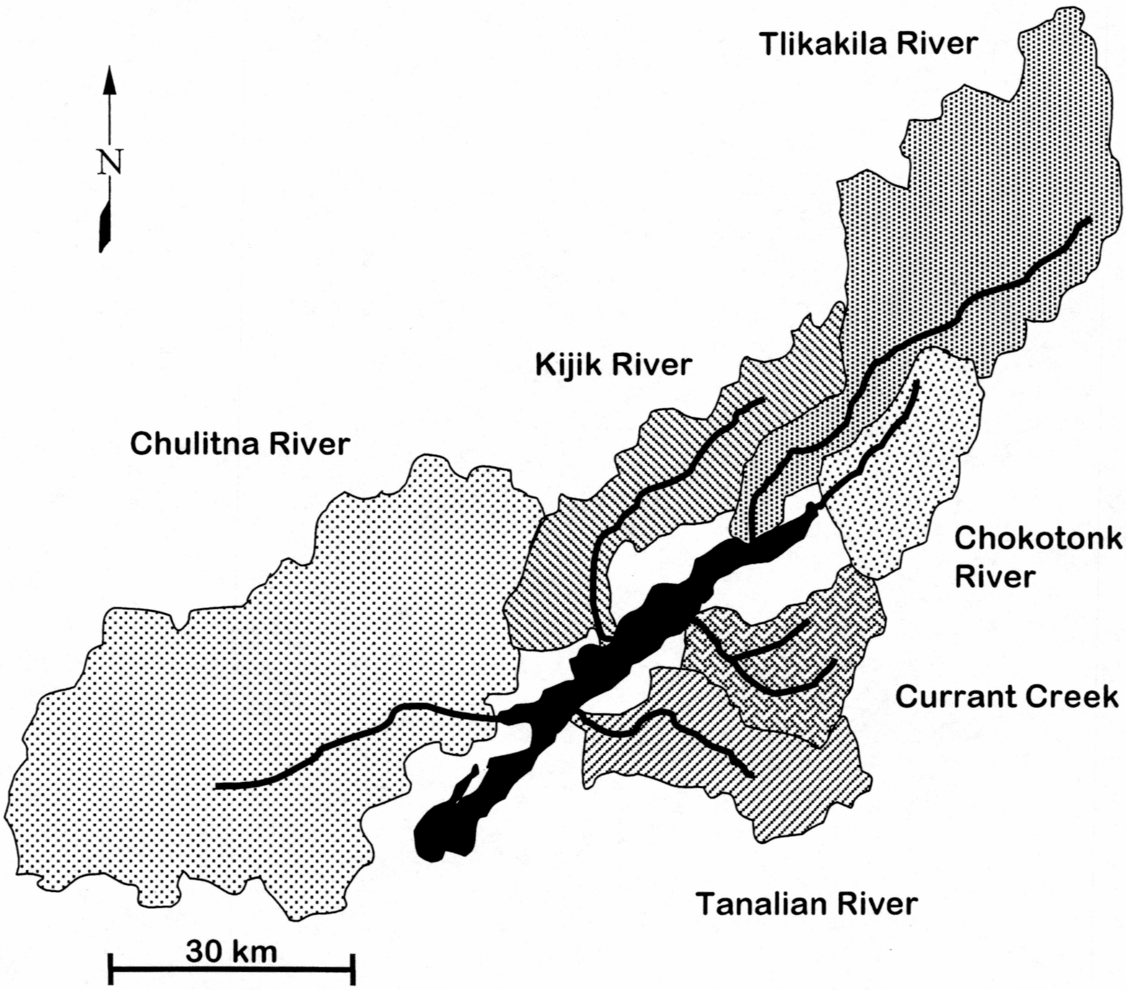

Figure 2. Major tributaries to Lake Clark and their watersheds.

Table 1. Characteristics of tributary inputs to Lake Clark. [Based on data from Brabets (2002), May to September of 1999-2001.]

Tributary	Type	Discharge (m^3 s^{-1})	Temp (°C)	Suspended Sediment (mg L^{-1})	Basin Area (km^2)
Chokotonk River	glacial	7-62	0-10	9-211	436
Chulitna River	bog-fed	37-210	1-15	4-9	3000
Currant Creek	glacial	8-78	1-8	3-282	428
Kijik River	lake-fed	12-85	3-13	2-123	773
Tanalian River	lake-fed	5-168	5-14	1-5	532
Tlikakila River	glacial	1-340	0-10	5-710	1613
Lake Clark outlet	lake-fed	242-674	4-12	1-5	7629

METHODS

The lake was accessed by boat from Port Alsworth and samples collected at each of five stations (Figure 1). Samples were collected weekly between June 28 and August 17 of 1999 and once a month between June 8 and August 30 of 2000. At each station a mooring buoy was installed in conjunction with a lighter line on which to array temperature loggers through the water column (Figure 3). Station positions were predetermined, using Anderson's map (1969), by finding the geographic center of the deepest portion of each basin and the shallowest portion of each sill. Thus stations 1, 3, and 5 were located in the three main basins, and stations 2 and 4 were located on the intervening sills. Station coordinates were fixed using a Garmin GPS unit and confirmed by orientation with prominent landmarks. Station depths were confirmed using an onboard Lowrance depth finder. The order in which stations were sampled was randomized except when dangerous weather dictated when the most exposed stations be sampled.

Limnology Survey

Long-term temperature (°C) profiles were made using Onset data loggers arrayed along the smaller of the two buoy lines at each station (Figure 3). HOBOtemps, held inside a submersible polycarbonate case, were used down to 120 m. The remaining depth was covered with Stowaway Tidbit temperature loggers. One logger was located at 5 m depth and the rest at 18-m intervals to the bottom. The loggers took hourly readings during the summer and every four hours during the winter. To prevent the loggers from being locked in the ice during winter, the buoys were partially deflated, the lines shortened and connected, and the entire apparatus submerged 5 meters. Three of the five buoy sets were successfully recovered the following spring by towing grappling hooks through the water column.

All remaining limnological data were collected by visiting the five sampling stations over one or two days. Detailed, short-term profiles of temperature, along with

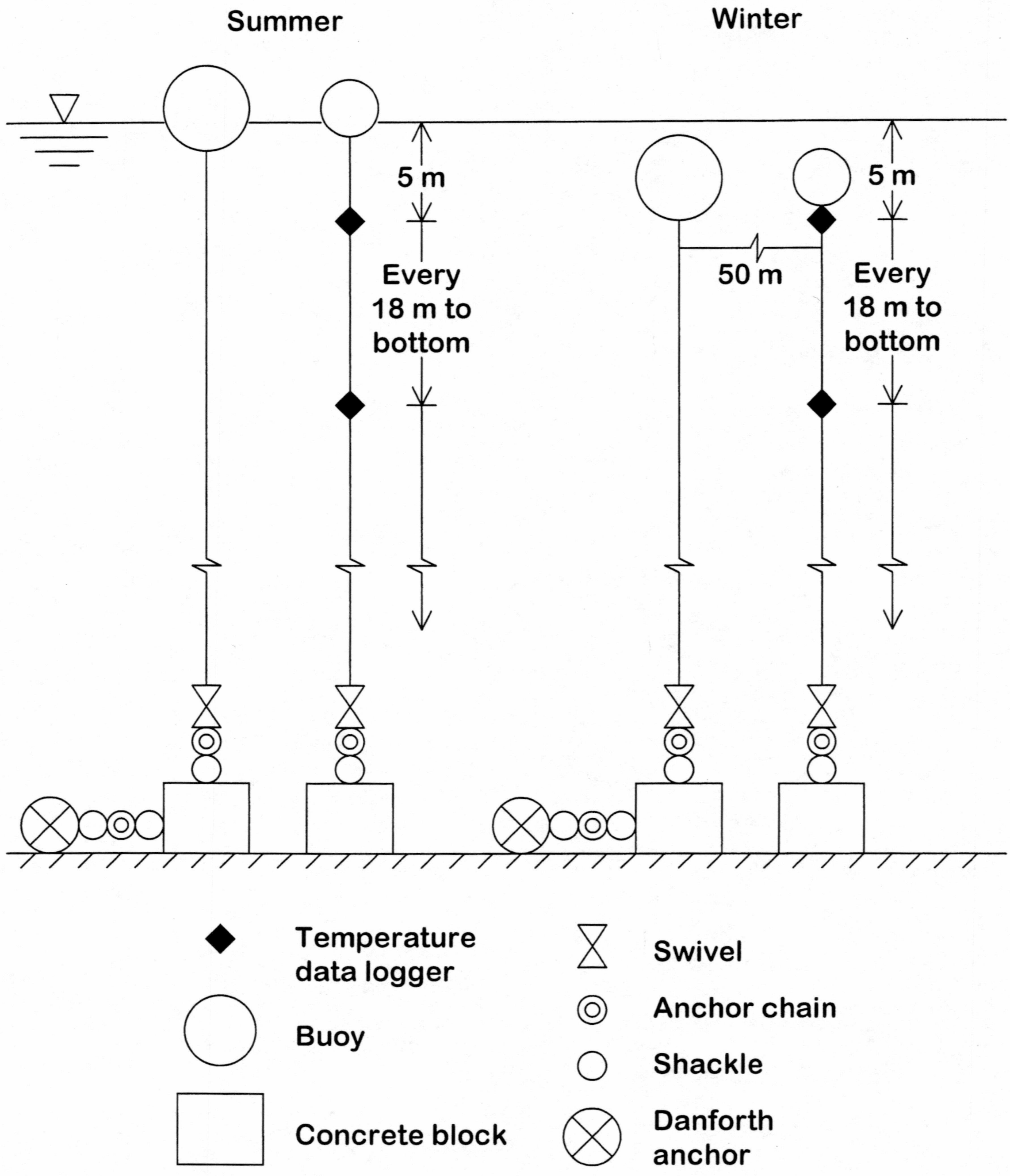

Figure 3. Design for mooring and instrument buoy lines.

oxygen (mg L^{-1} and % sat.), pH, conductivity (μS cm^{-1}), and redox potential (mV), were taken with a Hydrolab Surveyor 4, equipped with 200 m of cable and a Minisonde. Measurements were taken every meter from 1-5 m, every 10 m between 5 and 50 m, and every 20 m between 50 and 200 m. All sensors on the Hydrolab meter were lab-calibrated at the beginning of each field season and again every month. The Hydrolab meter was field-calibrated at the lake surface for dissolved oxygen and depth to account for barometric pressure, and conductivity was automatically corrected to 25°C by the meter. A YSI 3800 Water Quality Logger was used to confirm calibrations and as a backup meter.

Light measurements were taken with a light meter (kLux) and a Secchi disk. The light meter was a LI-COR LI-180, equipped with an LI-192SA Underwater Quantum Sensor that measured photosynthetically active radiation in the 400-700 nm range. The meter was lowered to immediately below the water's surface, a reading taken, then lowered by 1-m intervals until the 1% incident light level was reached. The vertical attenuation coefficient of downward irradiance, K_d, was calculated as the slope of the line of best fit in a plot of log-transformed light intensity versus depth. The Secchi depth (m) was measured with a standard 20-cm weighted disk, using standard procedures (Carlson, 1995). Apparent color measurements (F1-F11) were taken against the white background of a Secchi disk at a sufficient depth for comparison with a KAHLSICO Forel-Ule handheld scale.

Triplicate water samples for determination of true color (platinum-cobalt units), turbidity (nephelometric turbidity units, NTU), suspended solids (μg L^{-1}), and algal biomass as chlorophyll-*a* (μg L^{-1}) were taken by slowly lowering 50 m of Tygon tubing into the lake, then blocking the free end, retrieving the tubing, and emptying the water it contained into an insulated cooler. The hose had an internal diameter of 1.3 cm, and this procedure generated approximately 6 L, integrated over 50 m depth range. One liter of this sample was used to measure suspended solids and phytoplankton biomass, and 10 mL was used for turbidity. Turbidity was analyzed on the boat using a HACH 2100P portable turbidimeter with matched vials. The liter samples were transported to on-shore facilities in Cubitainers inside an insulated cooler, then filtered across a Gelman Type A/E glass fiber filter. The filtrate was measured for true color using a HACH DR/700 Colorimeter and 450 nm module, which is based on the Platinum-Cobalt Method (APHA et al., 1998). A saturated solution of $MgCO_3$ was pumped across the phytoplankton filters to make them alkaline, and both phytoplankton and suspended sediment samples were frozen over desiccant for transport to the University of Alaska Fairbanks and final analysis. At UAF the phytoplankton samples were analyzed for total chlorophyll-*a* by mincing the filters with scissors, extracting in refrigerated 90% acetone overnight, and then measuring for fluorescence as described by APHA et al. (1998). Suspended sediment samples were analyzed for their inorganic and organic fractions. Analysis followed the process of weighing, drying, and igniting the filters carrying the sediments, as described in APHA et al. (1998).

In July 2000 one sample was taken at each station for total nutrients ($\mu g\ L^{-1}$) and total dissolved nutrients ($\mu g\ L^{-1}$). Samples were collected and analyzed in accordance with the USGS National Water Quality Laboratory Schedule 1119 process (low-level nutrients + P + microkjeldahl P and N).

Zooplankton Survey

Zooplankton were collected in sets of multiple-depth samples, and fixed-depth samples. Samples from multiple depths were taken during day (8am-7pm) and night (10pm-3am) to describe zooplankton distribution and migration in the water column, and to determine the best fixed depth from which to sample. Multi-depth samples were hauled to the surface from the following depths: 10, 20, 30, 40, 50 m, and the bottom. A blind test was performed on the volume of settled animals to determine how deeply live zooplankton ranged, which indicated a maximum depth of 50 m. Further multi-depth samples were taken throughout the study to ascertain zooplankton distribution through the water column. Fixed-depth sampling was done in triplicate from 50 m in order to sample all living zooplankton and was used to more precisely measure abundance, distribution, biomass, taxonomic composition, and length-frequency. During 1999, multi-depth samples were taken in June and July, and fixed-depth samples were taken weekly from June through August. In 2000, both multi-depth and fixed-depth samples were taken once each month in June, July, and August.

All zooplankton samples were collected using a meter-long conical net with a 30-cm diameter mouth and 102-μm mesh. The net was hauled vertically through the water column by winching a demarcated cable at no greater than 1 m s^{-1}, and zooplankton were rinsed into a capture jar and preserved in 5-10% buffered formalin (Haney & Hall, 1973).

Sample analysis of zooplankton was carried out by the lab of Dr. Asit Mazumder, at the University of Victoria, British Columbia, using a FOCAL 1L optical plankton counter (OPC) and a zooplankton imaging process (ZIP). The OPC sized zooplankton by measuring the shadow generated as they passed through a beam of light. This information is converted to an equivalent spherical diameter (ESD) and included a total animal count. In the ZIP, sub-samples were taken and individual zooplankton were identified and measured, then weighed as a group. The ZIP used a digital camera mounted on a dissecting microscope to feed length-calibrated images to a user-interactive monitor, where images of zooplankton were manually marked and automatically measured. ZIP information was used to determine zooplankton biomass and taxonomic composition. Biomass was calculated by Dr. Mazumder's lab using published length-weight relationships. Zooplankton density and biomass at depths greater than 10 m were calculated by first accounting for the volume filtered, then subtracting out the zooplankton in the overlying water. All samples were run on the OPC, but only one-quarter were run through the ZIP due to budgetary constraints.

Quality Assurance/Quality Control

All turbidity, suspended solids, chlorophyll-*a*, true color, and 50-m zooplankton samples were taken in triplicate to ensure analytical precision. Some zooplankton multi-depth samples were also replicated. All field instruments were calibrated before each visit to the lake and then again at the manufacturer's recommended intervals. When acceptable, calibrations were made on the boat immediately before the instrument was used. During each sampling season at least two randomly chosen temperature loggers were hung next to each other to ensure recording precision. Laboratory instruments were calibrated at the start of each analytical set, and calibration was checked between every sample.

Samples were relabeled with unique random numbers before being analyzed to prevent observer bias. Samples analyzed by outside laboratories were similarly renumbered. In addition, before the zooplankton samples were shipped, three bottles were sub-sampled and analyzed for species composition, abundance, length-frequency, and wet weight. The results generated by Dr. Asit Mazumder on the same samples were sufficiently similar to my results.

RESULTS

Limnology

Temperature—During this study Lake Clark never developed a true thermocline (Figures 4 & 5), which is defined by Wetzel (1983) as a change of at least 1°C per meter of depth. The lake weakly stratified during both summers and inversely stratified in the winter, showing a maximum temperature gradient of 0.36°C m^{-1} on July 26, 1999 at the outlet basin (station 1). The water column became isothermal twice during the study: once in October/November and again in May (Figures 6 & 7). Stratification began in late May/early June and ended in October. Inverse stratification began in December and ended in April. Mid-summer cooling was seen at stations 1, 3, and 4 in 1999 and at station 5 in 2000.

Lake Clark exhibited complex thermal structure, especially during the summer months (Figures 8-11). The lake showed a thermal gradient with the same temperature maxima taking one month longer to develop at station 1 than at station 5 in 1999. The reverse was true of 2000, except that the time lag was two weeks. Lake temperatures were variable across stations during the summer, but not in winter. It was not consistently warmer or cooler at any one station, although the outlet basin (station 1) generally exhibited the greatest temperature extremes. Alternating layers of 3- and 4-degree water were seen at depth during the winter (Figures 9 & 10), although this fluctuation is likely explained by temperatures hovering near 3.5°C, causing rounding errors. The maximum recorded temperature was 13.7°C, measured at 5 m on August 18, 1999 at the outlet basin (station 1). The minimum recorded temperature was 0.7°C, taken at 5 m during early January at the inlet and outlet basins (stations 1 and 5).

Oxygen, pH, and Conductivity—Epilimnetic oxygen levels were near saturation or were supersaturated throughout the study (Figures 12-15). During all of 1999 and June of 2000, oxygen levels in the metalimnion and hypolimnion were below saturation, but were still near 100%. In July and August of 2000, oxygen levels in the metalimnion and upper hypolimnion were well above the saturation point. Oxygen levels were often

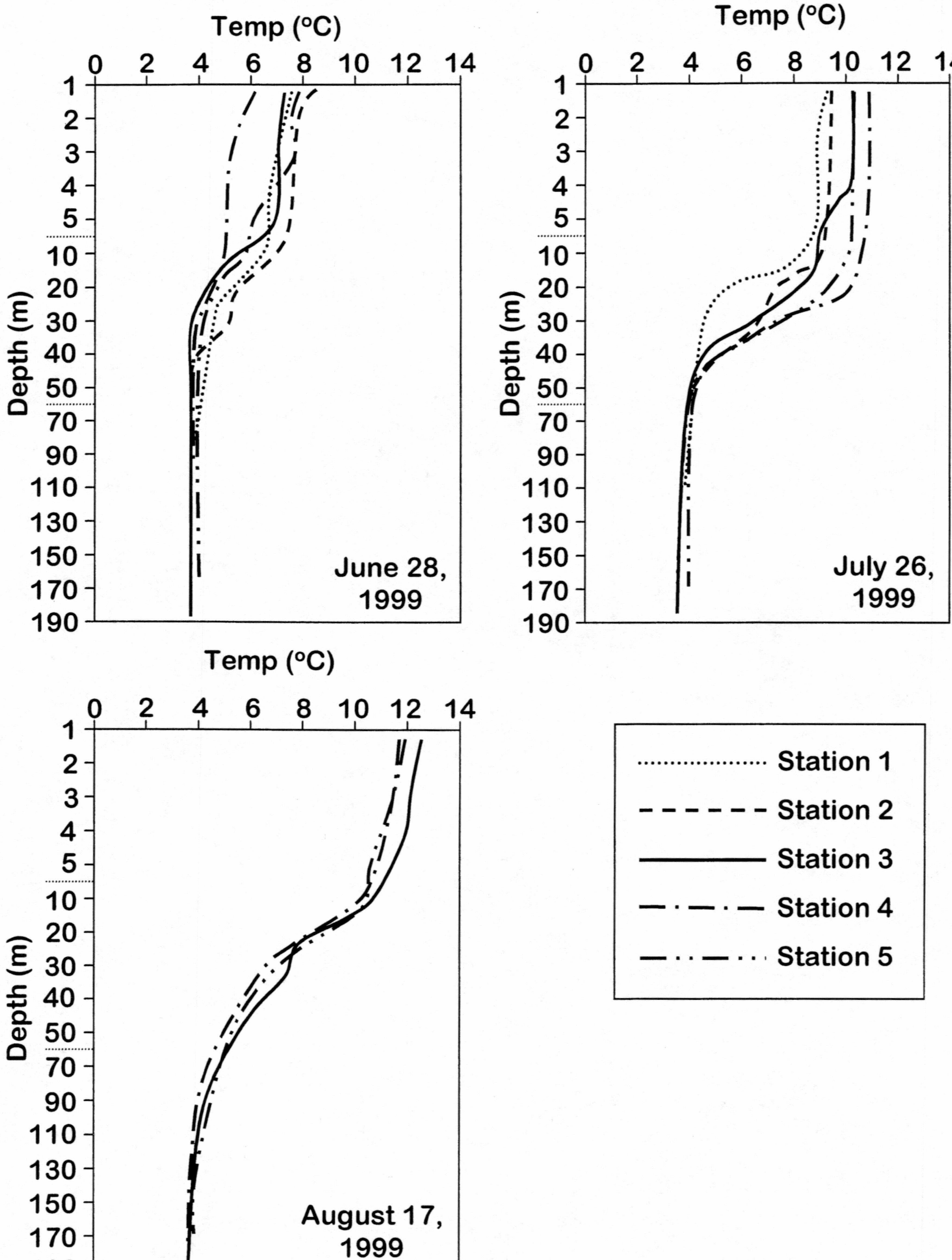

Figure 4. Temperature profiles from summer 1999.

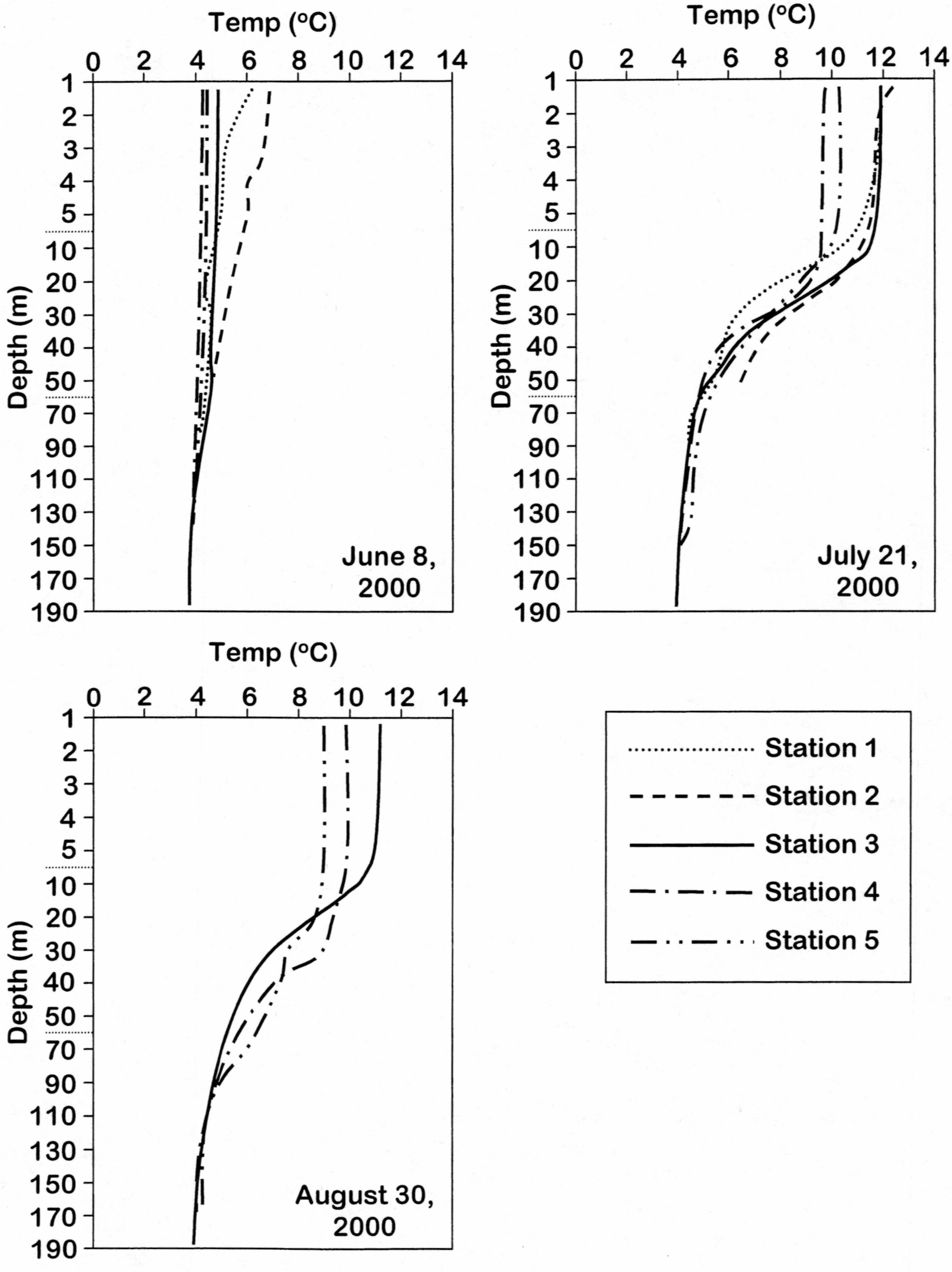

Figure 5. Temperature profiles from summer 2000.

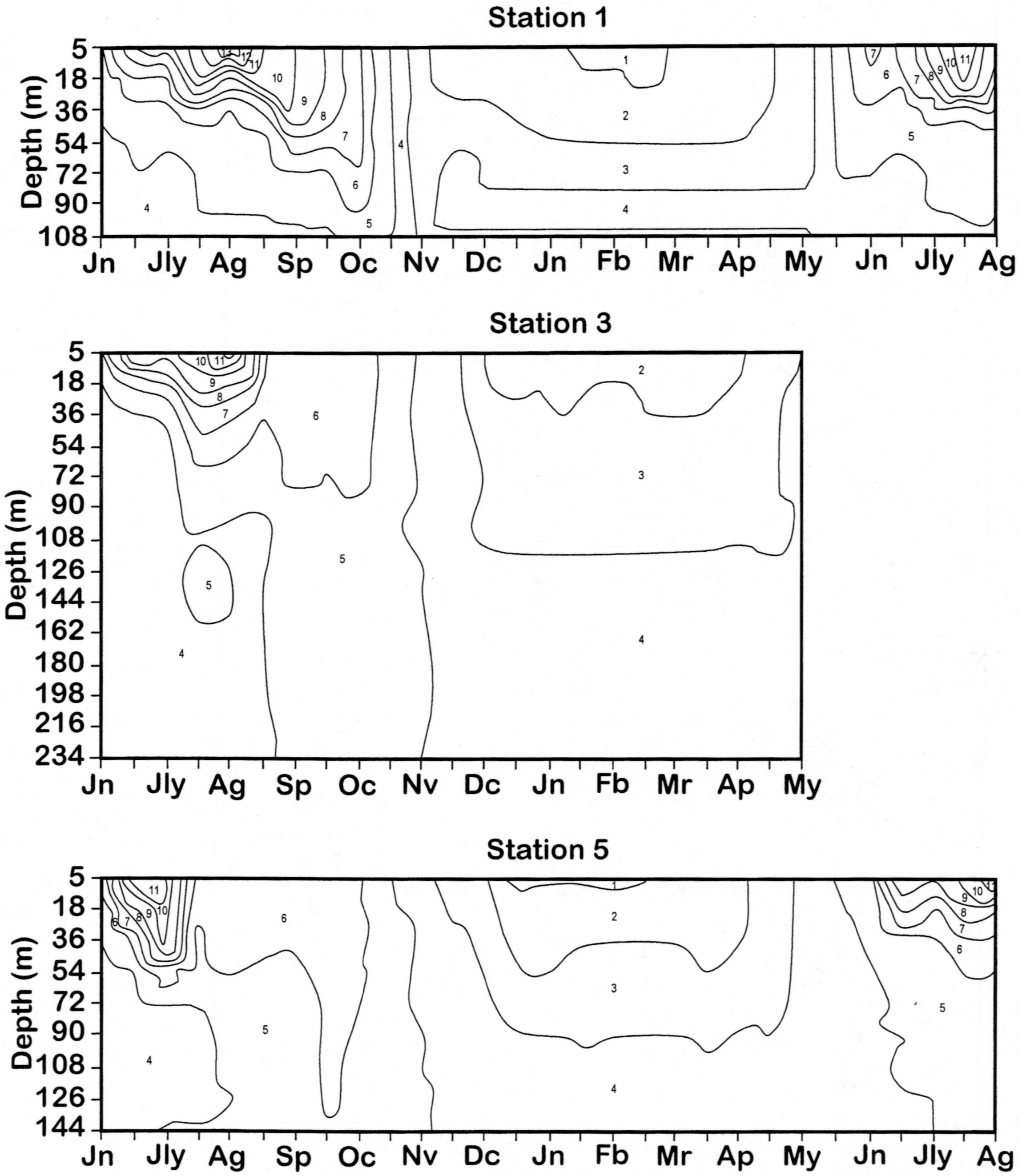

Figure 6. Seasonal isotherms (°C) for the three basin stations from early June 1999 to late August 2000.

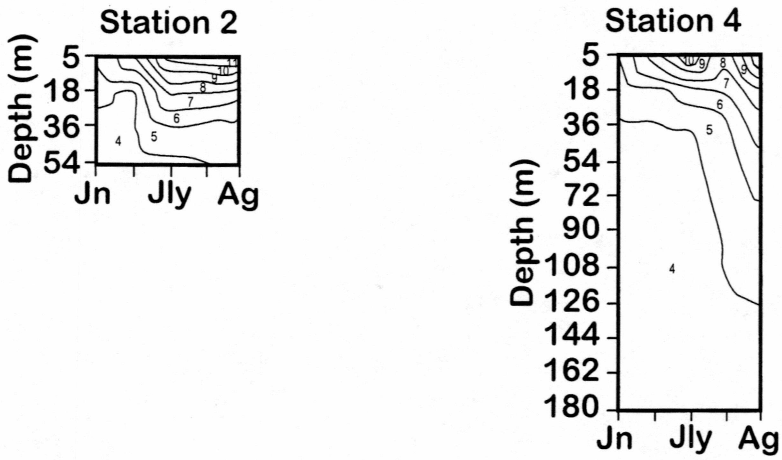

Figure 7. Seasonal isotherms (°C) for the two sill stations from early June 1999 to August 1999.

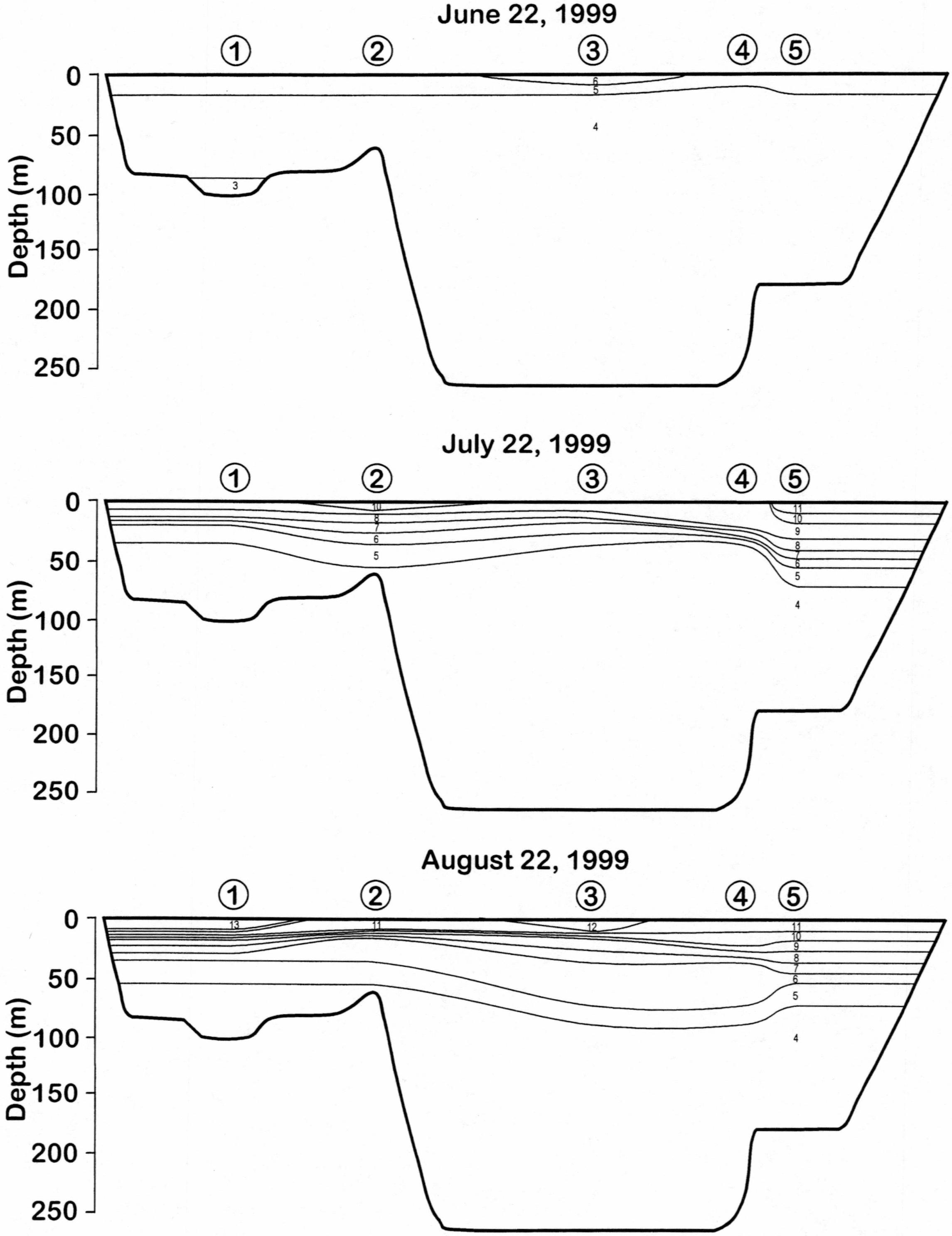

Figure 8. Lake cross-sections with isotherms (°C) for summer 1999. Isotherms drawn between stations as contours connecting equal temperatures.

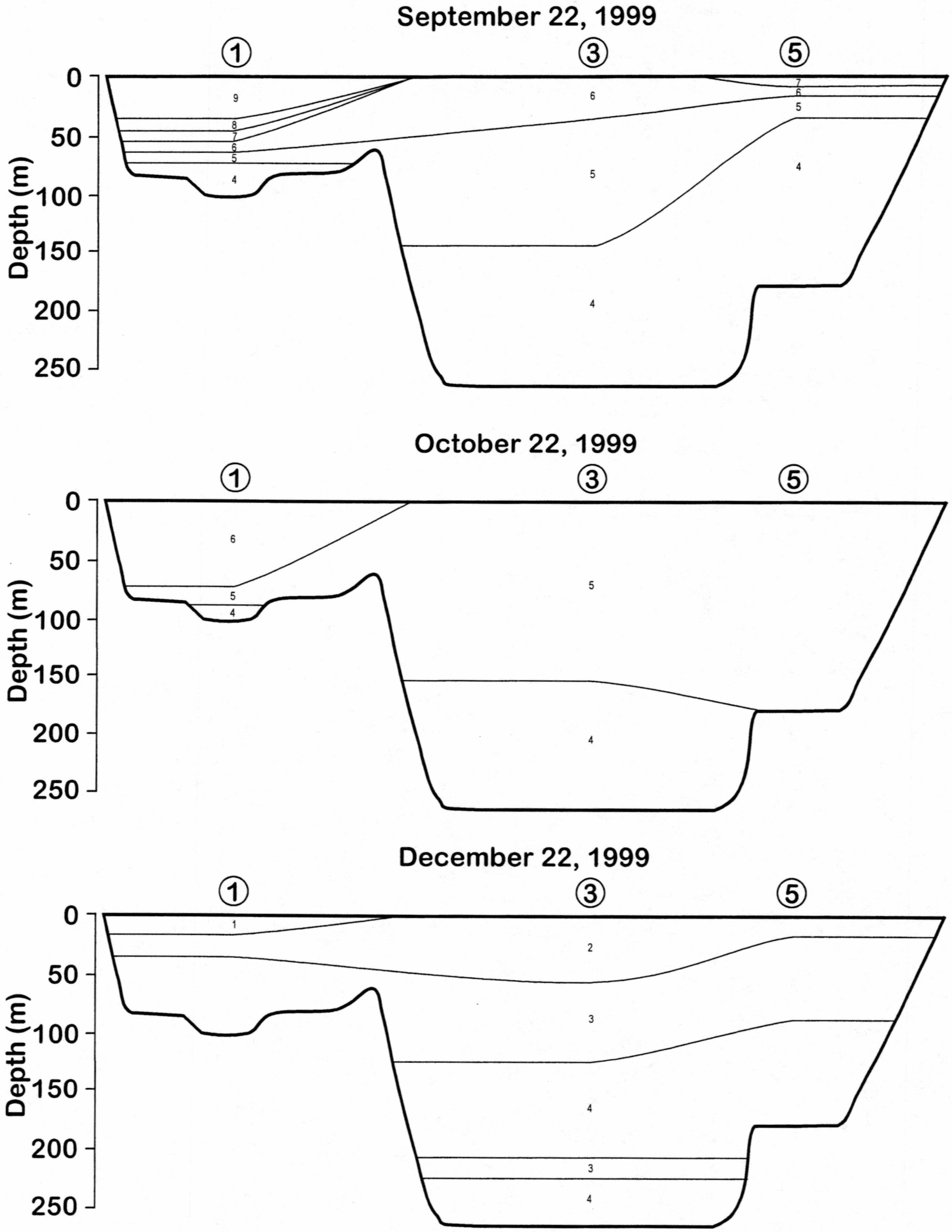

Figure 9. Lake cross-sections with isotherms (°C) for early winter 1999. Isotherms drawn between stations as contours connecting equal temperatures.

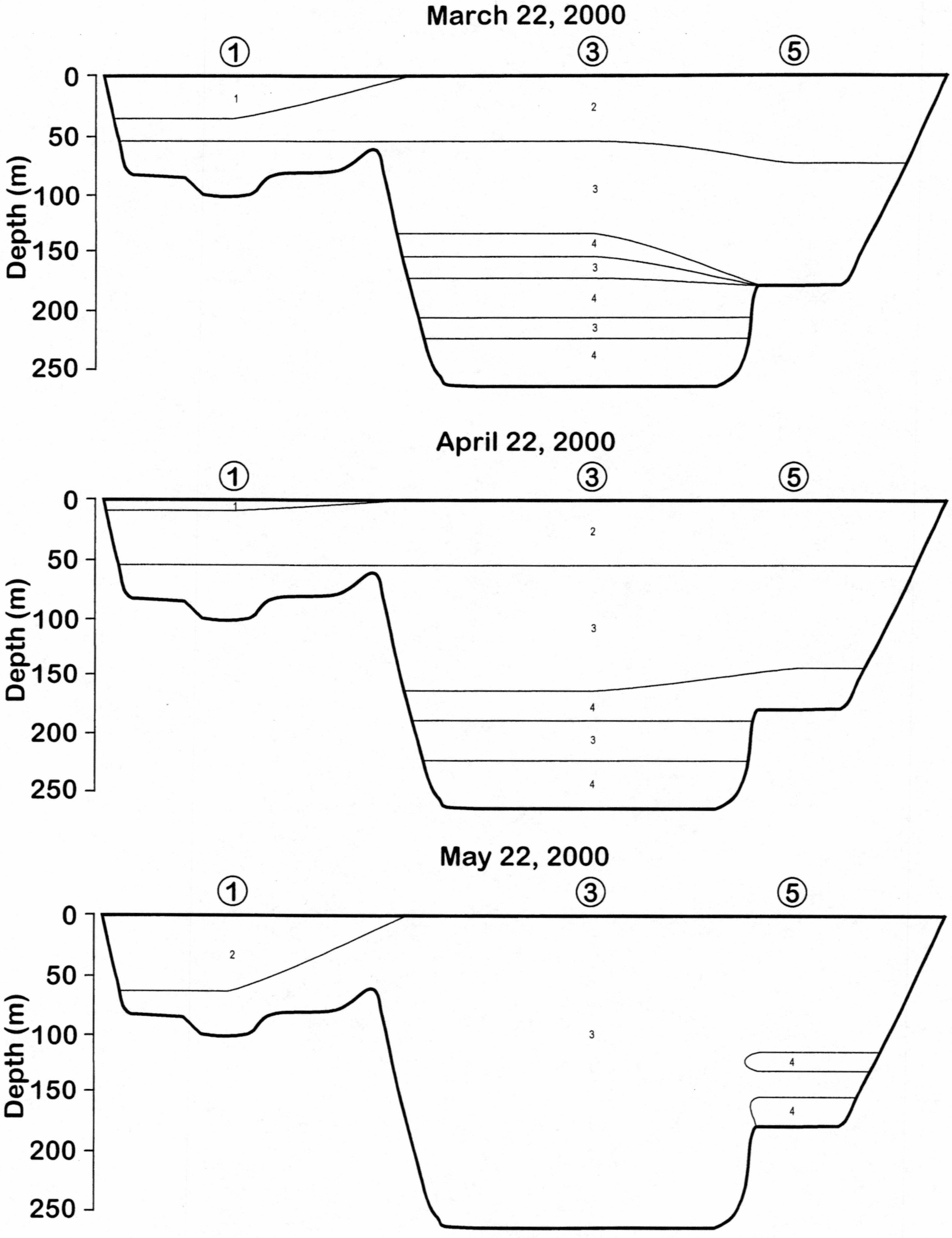

Figure 10. Lake cross-sections with isotherms (°C) for late winter 2000. Isotherms drawn between stations as contours connecting equal temperatures.

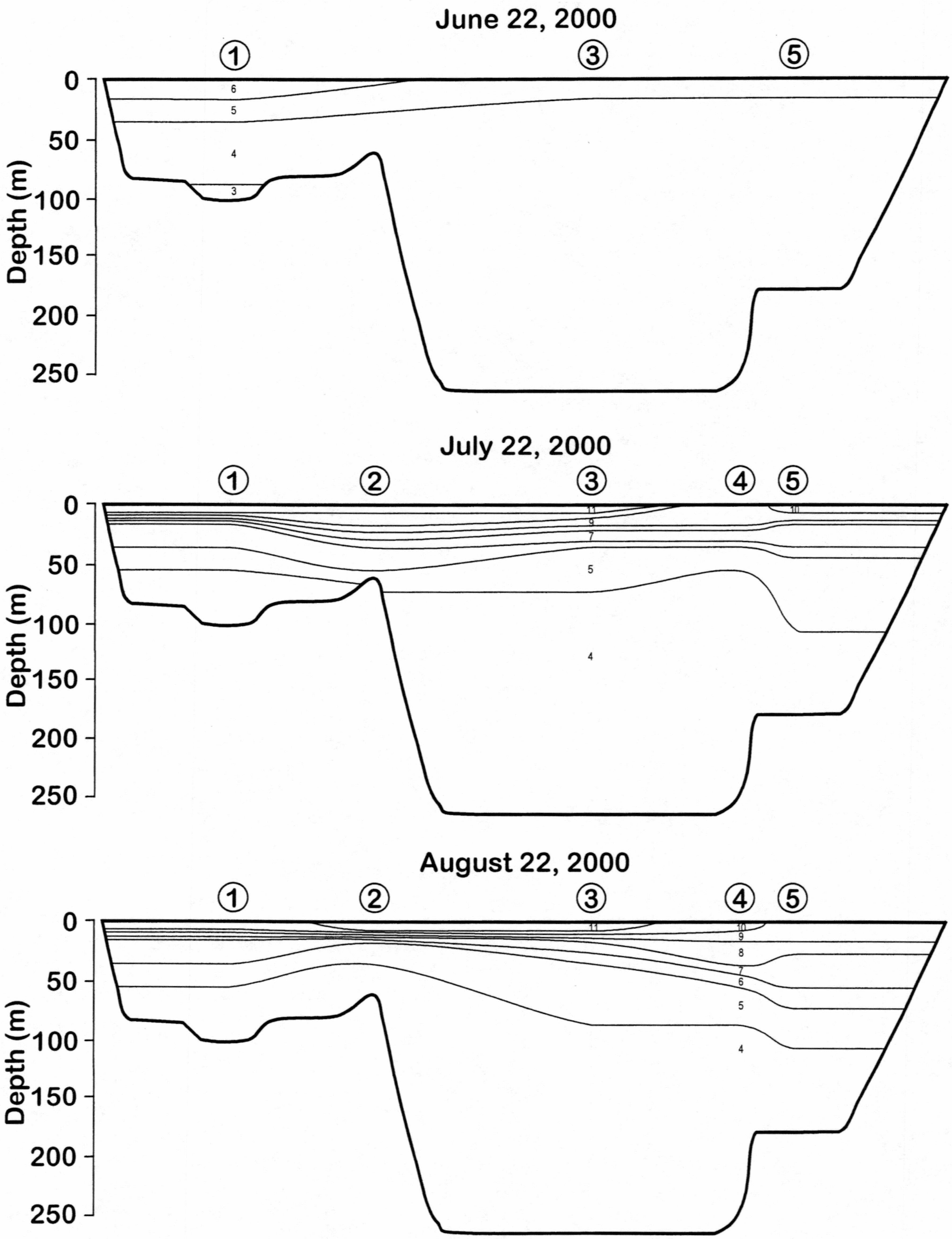

Figure 11. Lake cross-sections with isotherms (°C) for summer 2000. Isotherms drawn between stations as contours connecting equal temperatures.

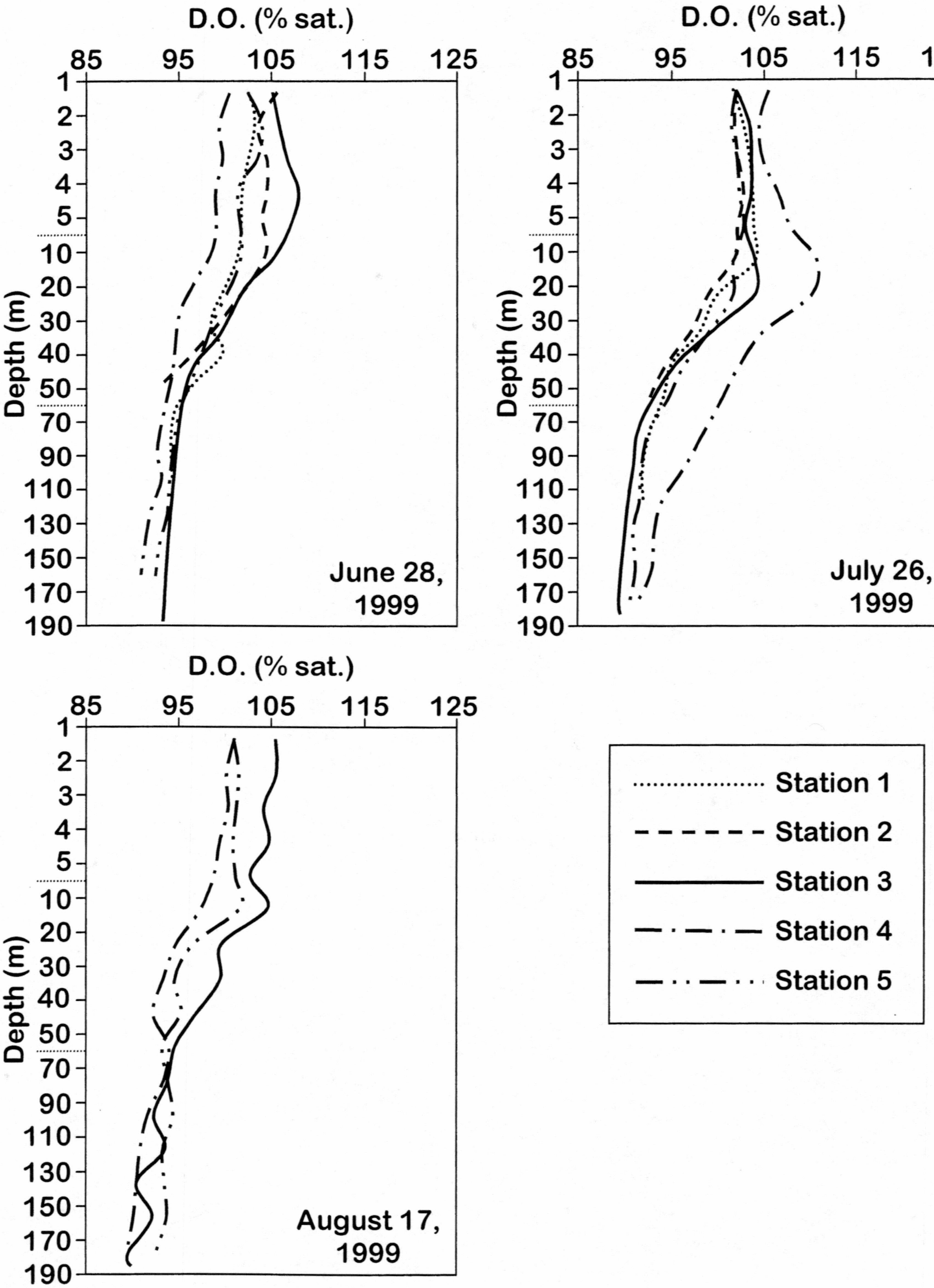

Figure 12. Dissolved oxygen percent saturation profiles for 1999.

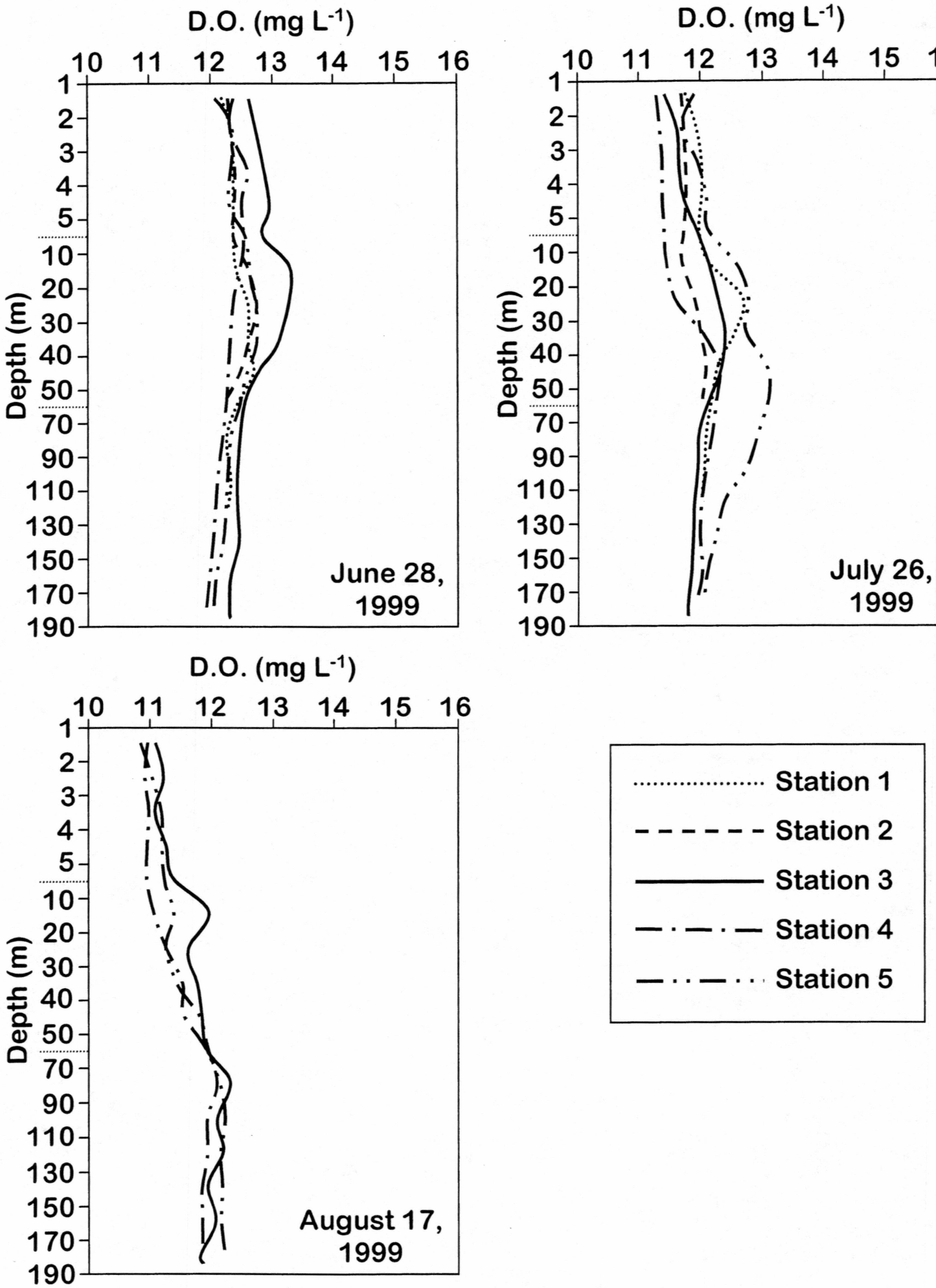

Figure 13. Dissolved oxygen concentration profiles for 1999.

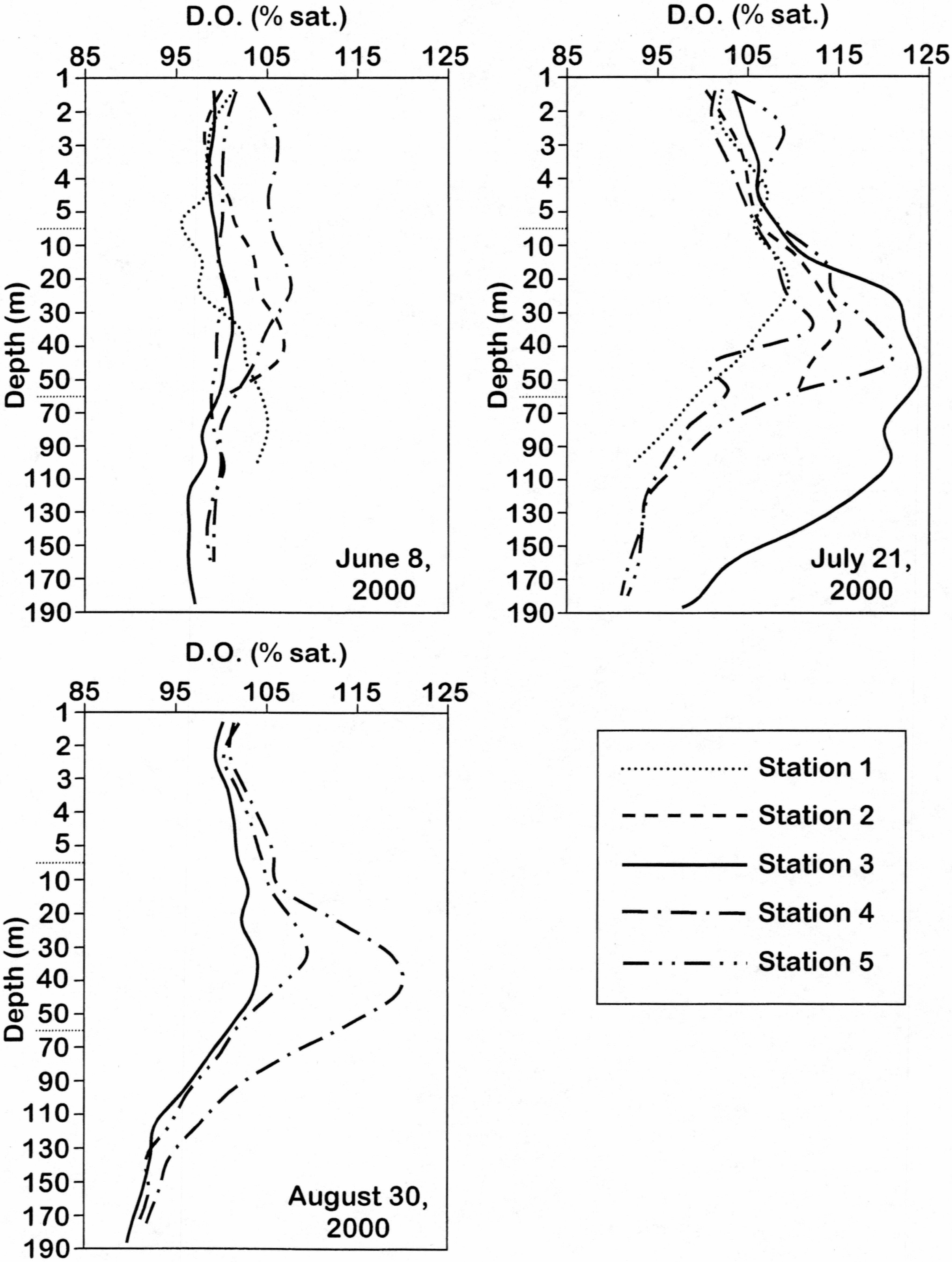

Figure 14. Dissolved oxygen percent saturation profiles for 2000.

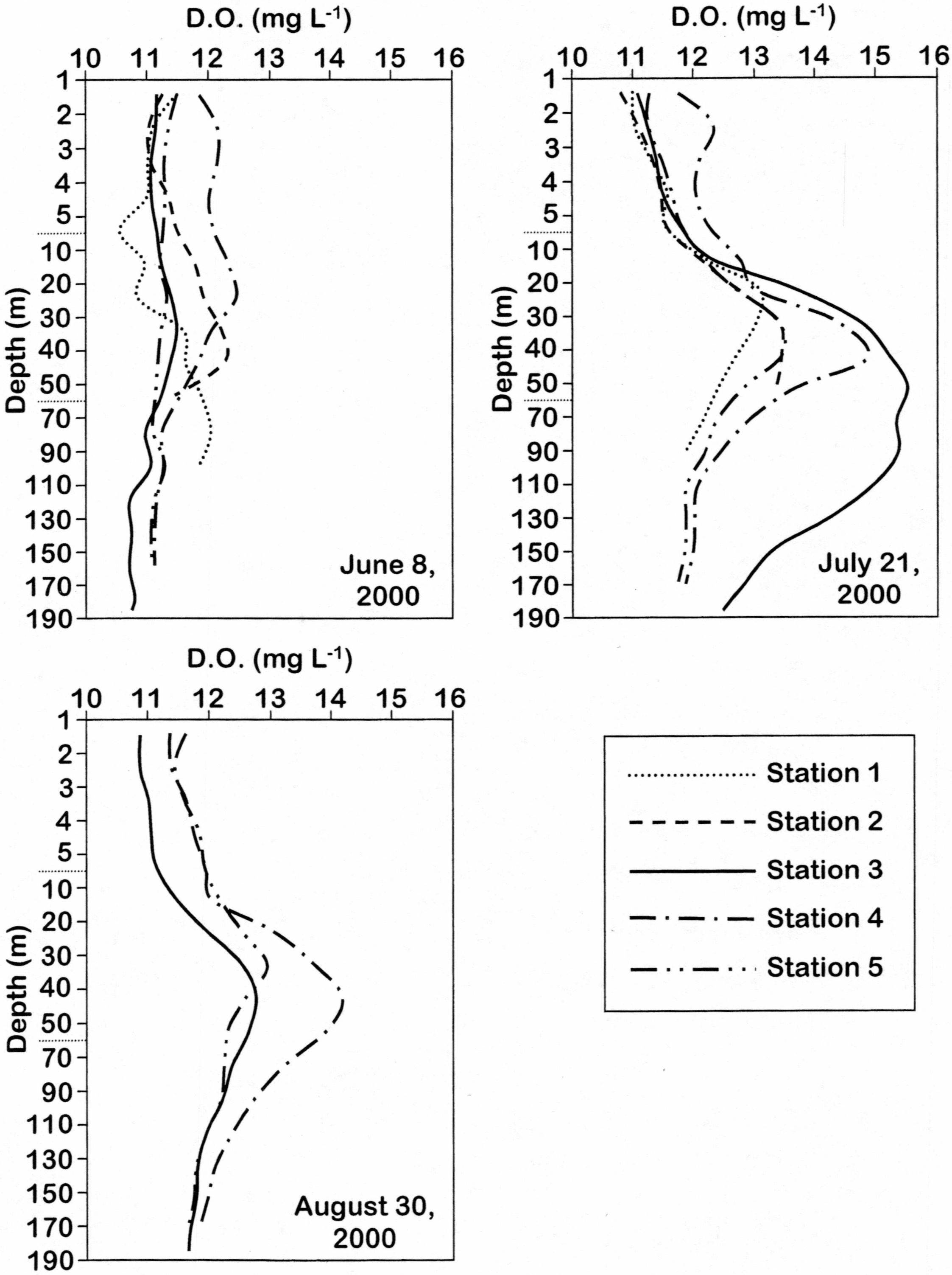

Figure 15. Dissolved oxygen concentration profiles for 2000.

higher at stations 3, 4, and 5 than at station 1, while station 2 varied in comparison to the other stations.

Throughout the study, pH values were slightly above neutral in the epilimnion, and decreased to neutral at a depth of 40-50 m (Figure 16). pH ranged from 6.8 to 7.8 and was usually between 7.1 and 7.4. Conductivity and redox potential were consistently orthograde, meaning they had straight, vertical profiles (Figure 16). Conductivity levels fell between 40 and 60 $\mu S\ cm^{-1}$ during both seasons, and redox potential ranged from 150-500 mV during the course of the study.

Light and Turbidity—Secchi depth ranged from 0.5-10 m, and generally decreased throughout the lake from June to late July, then increased slightly in August (Figures 17 & 18). The outlet basin (station 1) gave consistently deeper Secchi readings. Spatial and temporal changes in compensation depth, or depth to which 1% of incident light reaches, followed the same patterns as Secchi depth. The coefficient of vertical light attenuation, called the extinction coefficient or K_d, also matched Secchi depth. 61% of the variation in K_d was explained by turbidity ($p < 0.0001$).

Turbidity for all stations was near one NTU during June, then increased rapidly in July in the upper-lake areas (stations 4 and 5) to as high as 11 NTU (Figures 19 & 20). From July through August turbidity readings graded from high at the input end (station 5) to low at the outlet (station 1). Inorganic suspended solids explained 81% of the variation in turbidity ($p < 0.0001$), but organic suspended solids showed no such relationship.

Phytoplankton and Nutrients—Algal standing crop, measured as chlorophyll-*a* concentration, ranged from 0.5 to 1.5 $\mu g\ L^{-1}$ (Figures 21 & 22). Amounts of chlorophyll-*a* were consistently higher at the outlet end of the lake (stations 1 and 2) and generally peaked in late July/early August. Algal standing crop at stations 3, 4, and 5 remained near 0.6 $\mu g\ L^{-1}$ over both seasons. All nutrient concentrations were at or below the detection limit except nitrite+nitrate (Table 2).

True color fluctuated between 0 and 30 platinum-cobalt units and apparent color (Forel-Ule) ranged from F4 to F11 (Figures 21 & 22). No significant relationships existed between true color, apparent color, and chlorophyll-*a* concentration.

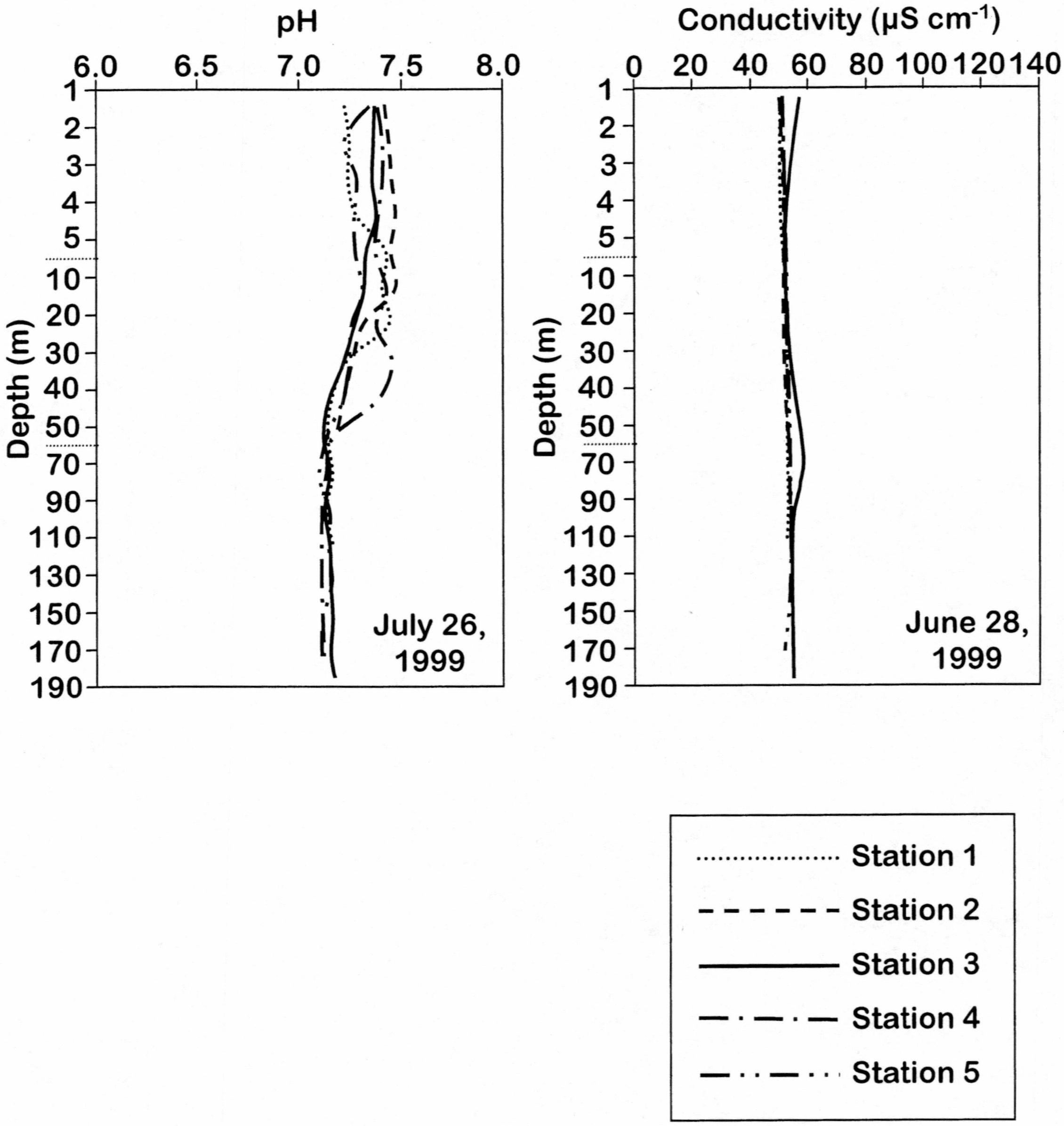

Figure 16. Example profiles of pH and conductivity.

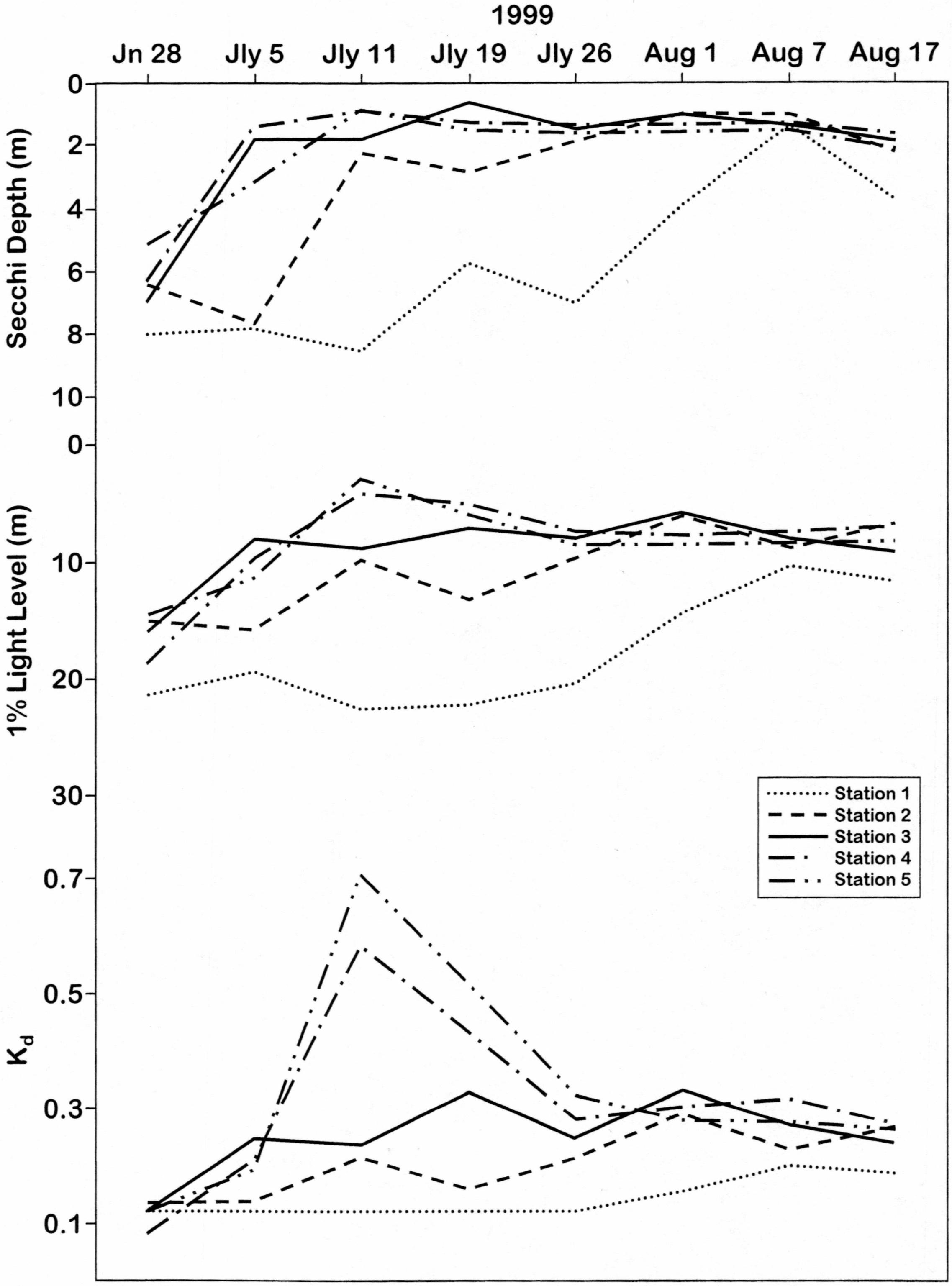

Figure 17. Secchi depth, compensation point, and extinction coefficients for 1999.

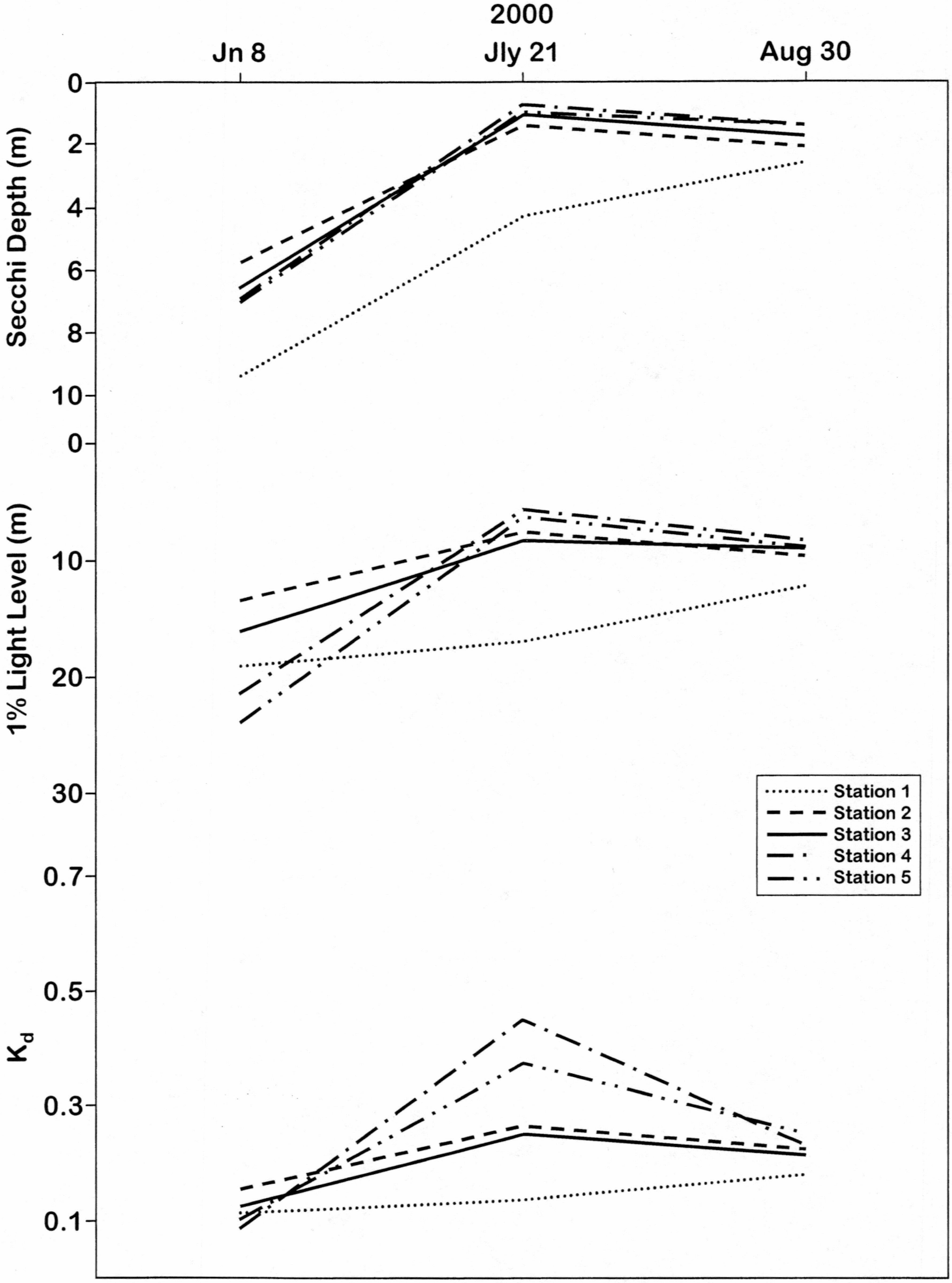

Figure 18. Secchi depth, compensation point, and extinction coefficients for 2000.

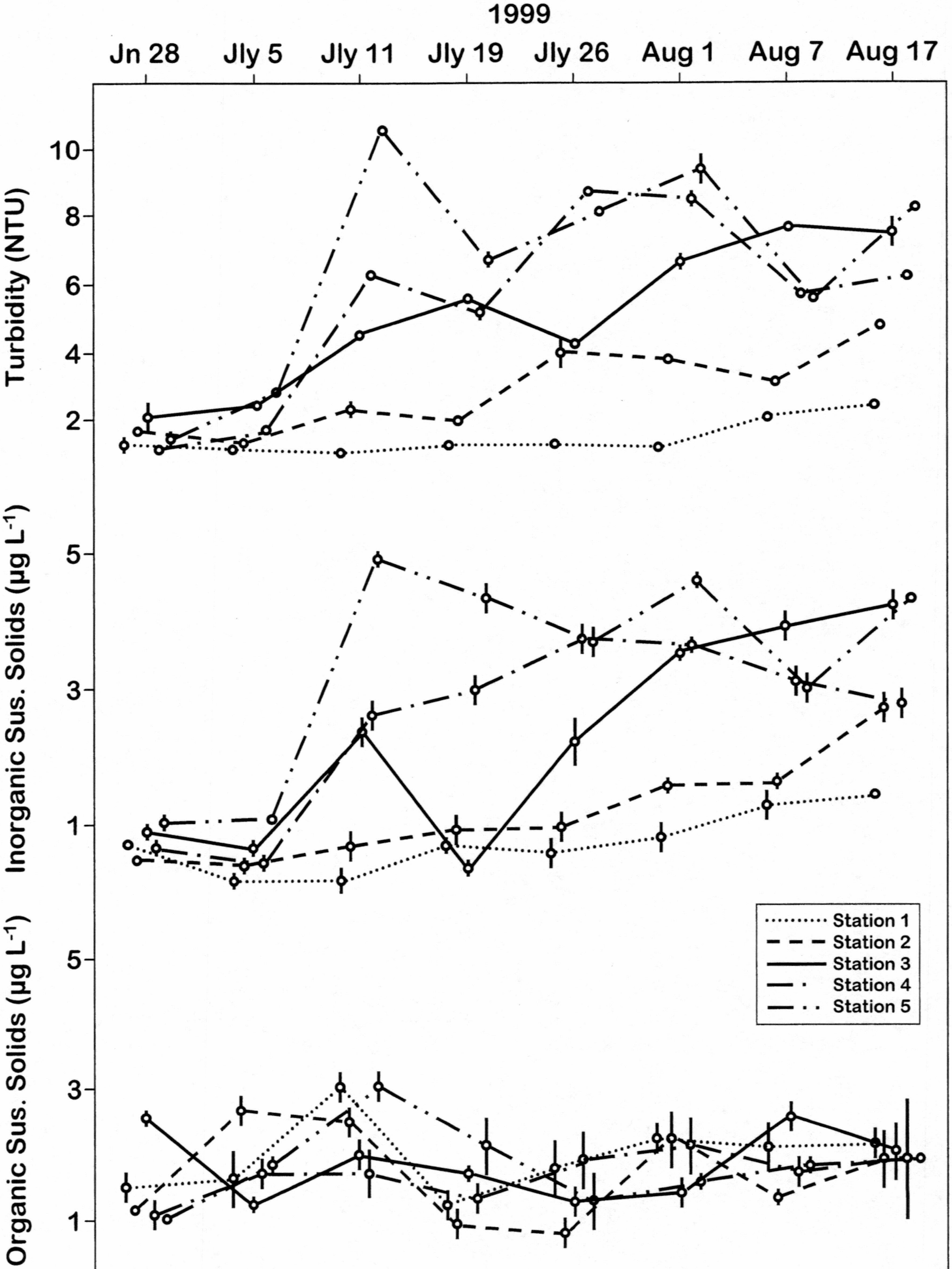

Figure 19. Turbidity, inorganic and organic suspended solids for 1999 (±SE).

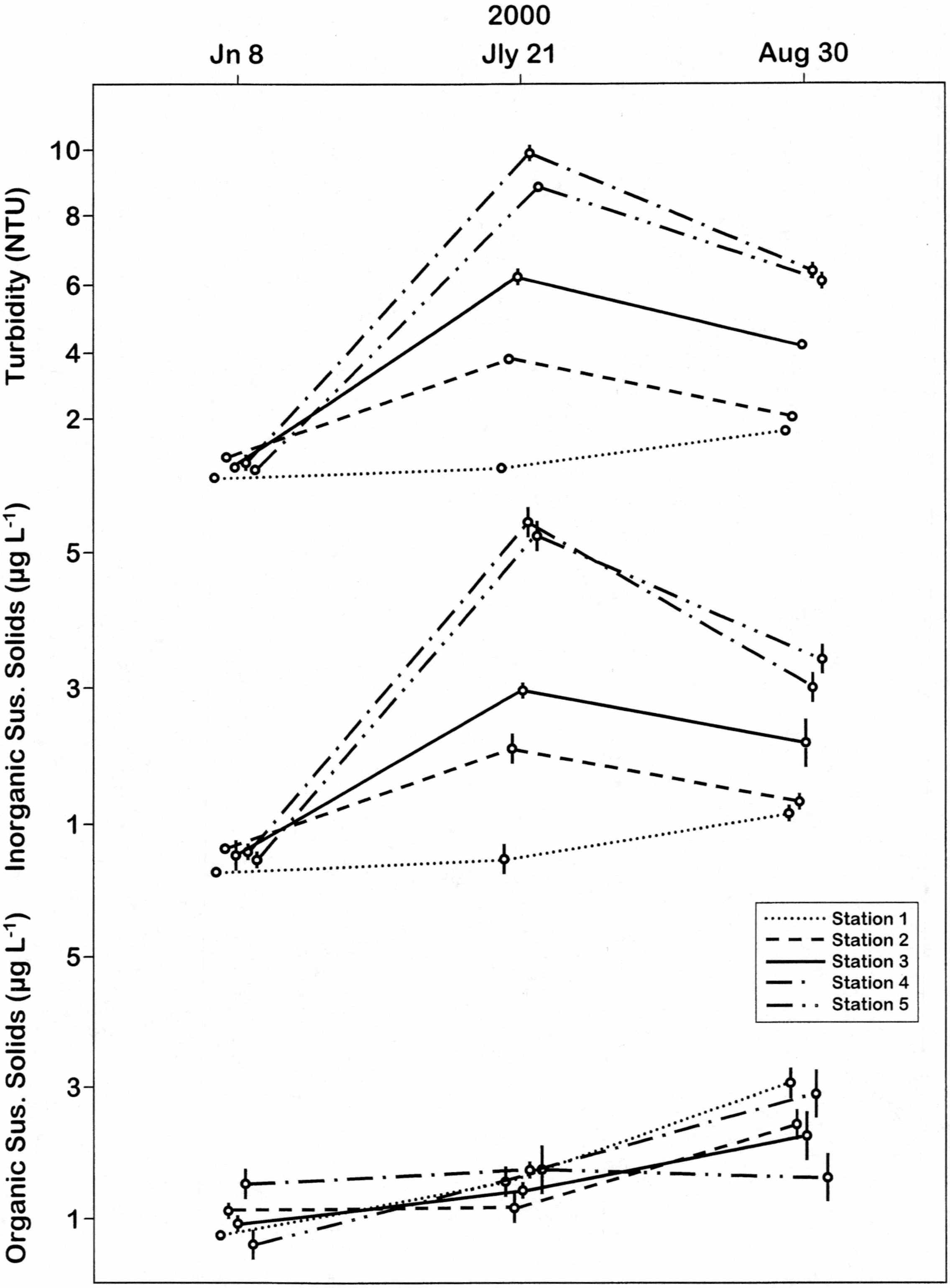

Figure 20. Turbidity, inorganic and organic suspended solids for 2000 (±SE).

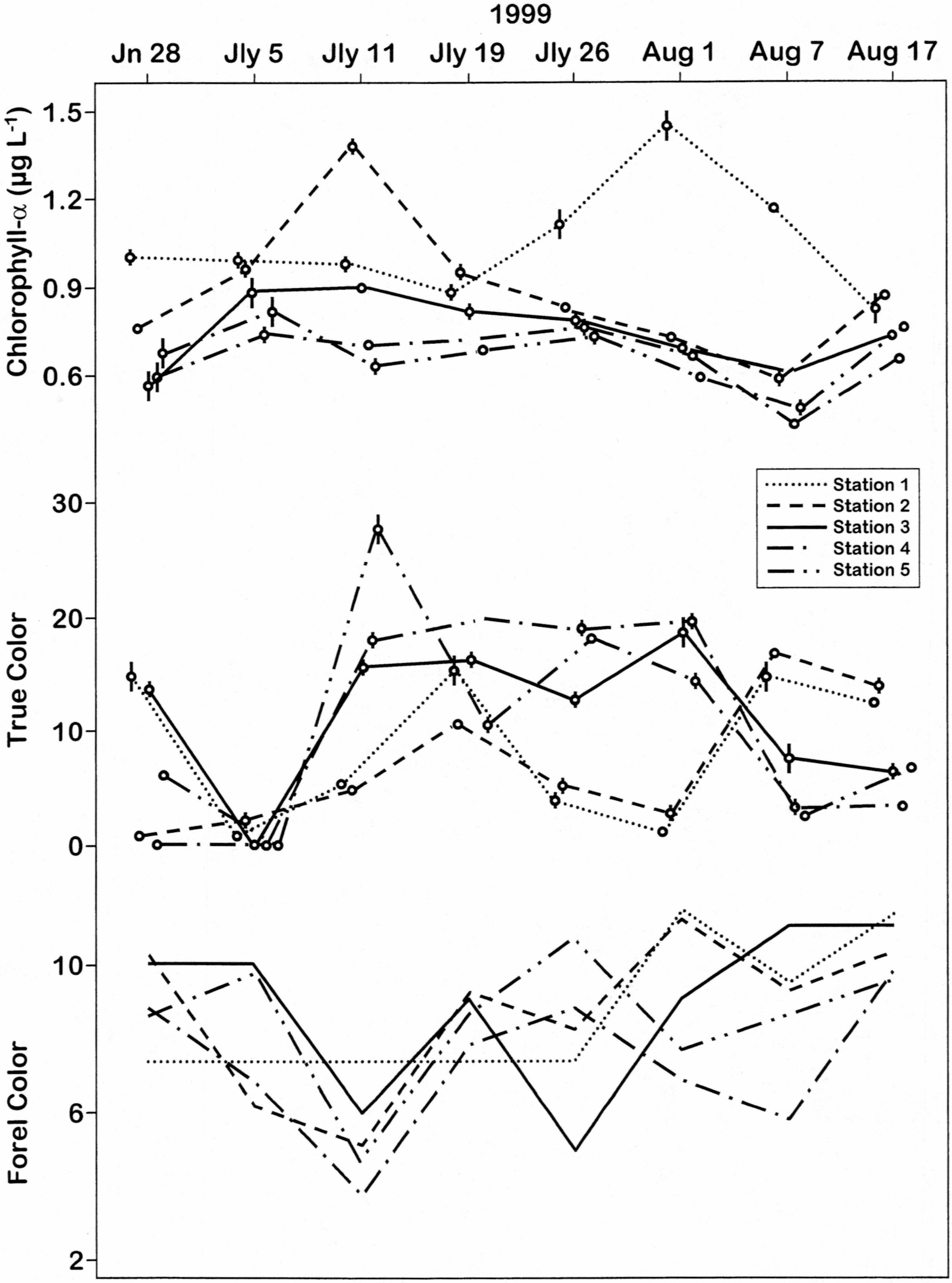

Figure 21. Total chlorophyll, true color, and apparent color for 1999 (±SE).

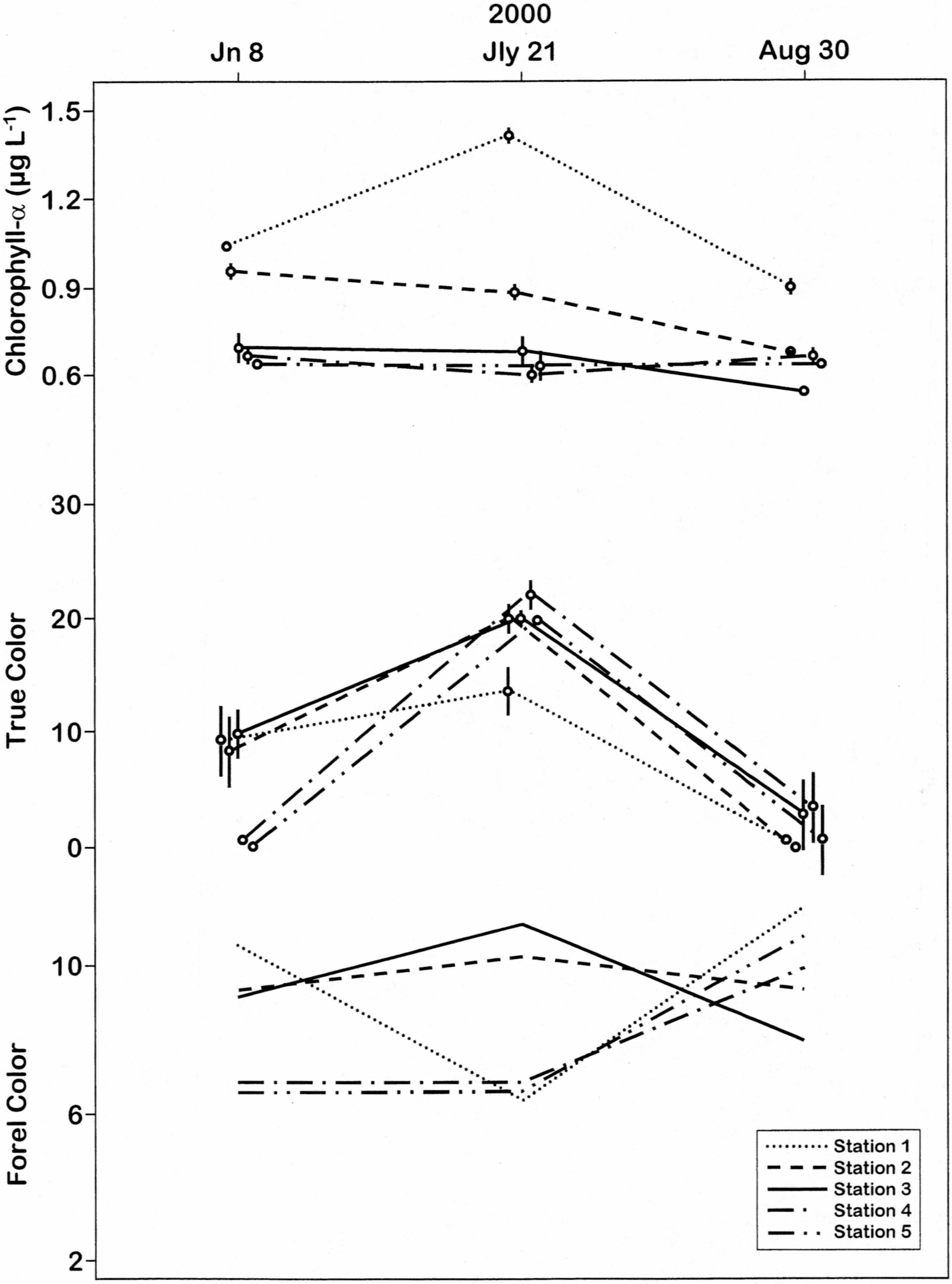

Figure 22. Total chlorophyll, true color, and apparent color for 2000 (±SE).

Table 2. Nitrogen and phosphorus concentrations ($\mu g\ L^{-1}$), taken July 21, 2000. (~ = near detection limit, < = below detection limit)

Station	Dissolved Nitrite + Nitrate	Total Dissolved Nitrogen	Total Phosphorus	Total Dissolved Phosphorus
1	183	191	<8	<6
2	180	186	~8	<6
3	183	183	~8	<6
4	186	186	9	<6
5	190	195	8	<6

Zooplankton

Abundance, Distribution, and Biomass—The highest density of zooplankton was consistently found in the central and inlet basins (stations 3-5) (Figures 23 & 24). Zooplankton densities across the lake ranged from less than one organism per liter to 10 per liter at station 3. Zooplankton densities at station 3 were as much as 2.5 times higher than station 1 in 1999, and as much as 5 times higher in 2000. Except for June of 1999, station 3 had consistently higher zooplankton densities than station 1, and was usually higher than station 5 as well. The bulk of zooplankton reside in the top 10 m of the water column, and nearly all are in the top 20 m, regardless of season, station, time of day, or limnological factors (Figure 23). No significant vertical migration of zooplankton was detected.

Zooplankton biomass tracked zooplankton density closely ($r^2 = 0.82$, $p < 0.0001$) and showed the same vertical distribution (Figure 25). The central basin (station 3) had up to three times more zooplankton biomass than the outlet basin (station 1) and as much as twice the biomass of the inlet basin (station 5). This relationship held true through time.

Taxonomic Composition—Nauplii and cyclopoid copepods accounted for 80-90% of zooplanton, with calanoid copepods making up the remaining 10-20% (Figures 26 & 27). *Bosmina* and *Daphnia* represented a fractional percentage of the community. Adult copepods represented 91-100% of zooplankton biomass (Figure 25). Nauplii made up 0-9% of biomass, and *Bosmina* and *Daphnia* accounted for 0-3%. Of copepods, cyclopoids made up 61-83% of the biomass, and calanoids the balance. The representative proportion of biomass for each taxon was generally stable across years, stations, and time of day. As depth increased, nauplii represented a greater proportion of the population while the percentage of adult copepods decreased. This relationship held true over both summers and no difference was seen between day and night.

In three sub-samples examined for species identification, all organisms encountered were classified as either *Cyclops scutifer* (Sars), or *Diaptomus gracilis* (Sars), which are cyclopoid and calanoid copepods, respectively. However, the *Cyclops*

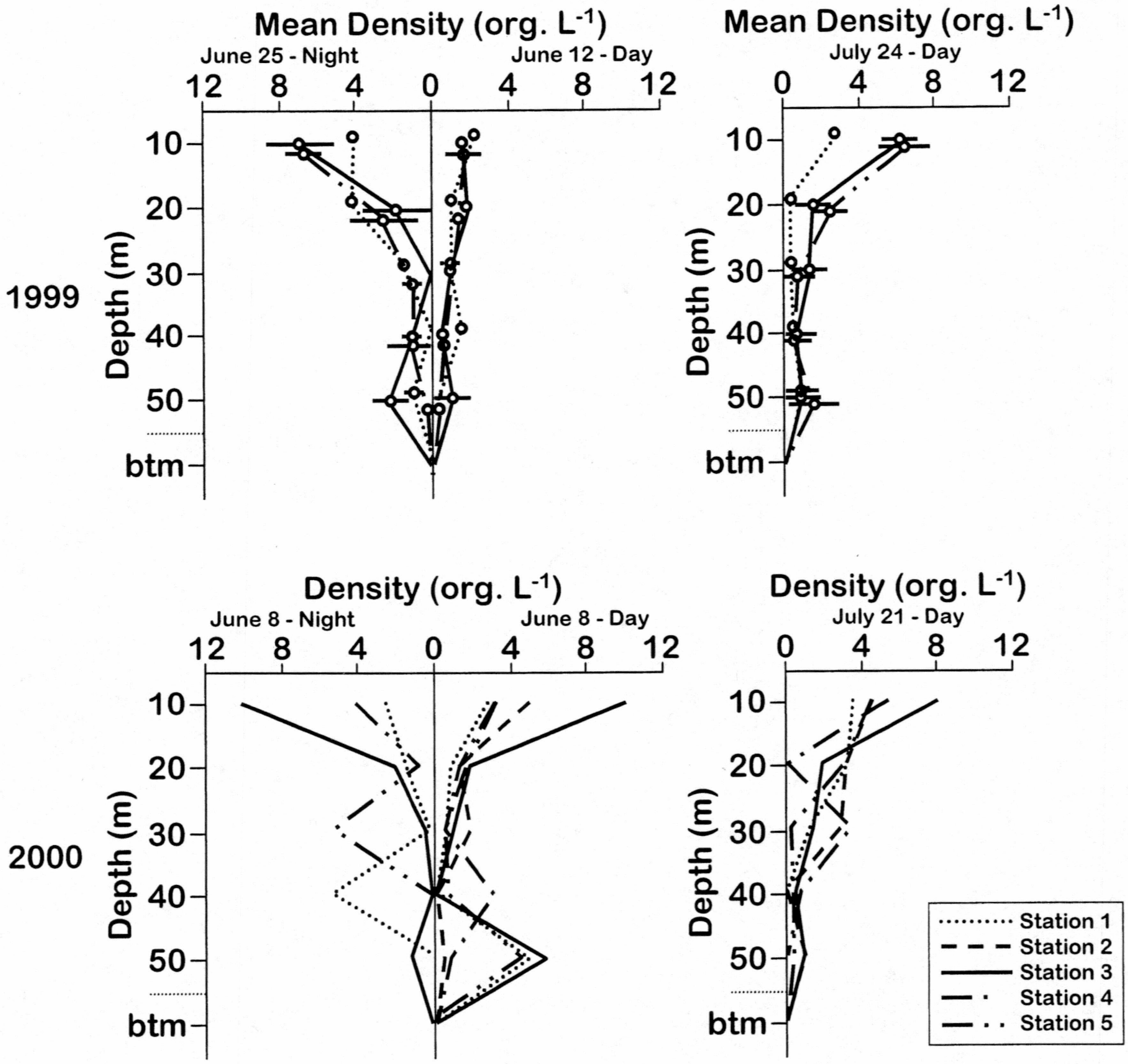

Figure 23. Zooplankton density versus depth, by station, for 1999 and 2000 (±SE). 1999 data had replication, but 2000 data did not. June samples for both years included night hauls, but July did not. In the June 1999 plot the day hauls were taken in early June and the night hauls in late June. Day hauls in 2000 were from all five stations, and the rest were from stations 1, 3, and 5.

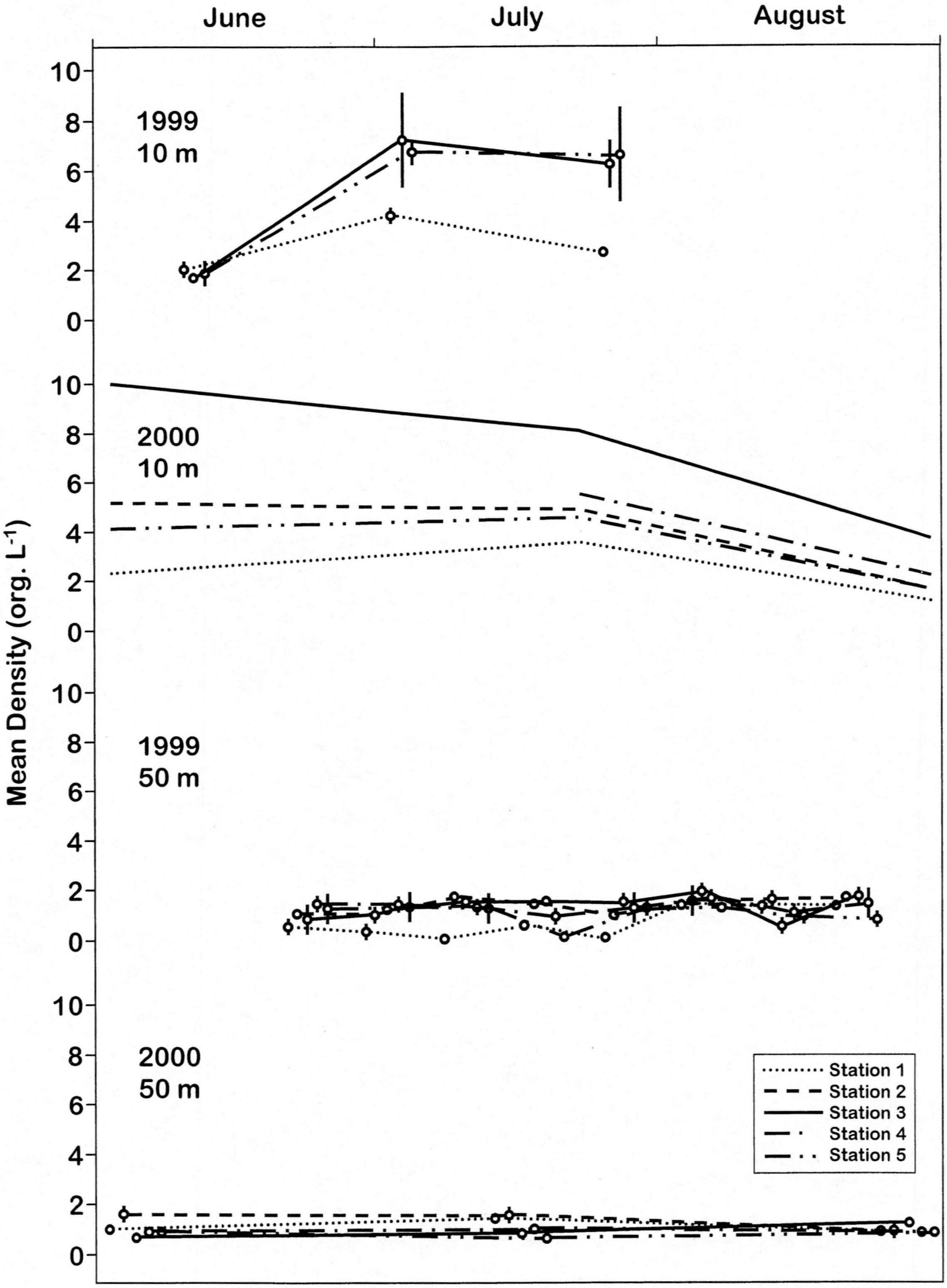

Figure 24. Zooplankton density over time, at 10 and 50 m, during 1999 and 2000 (±SE).

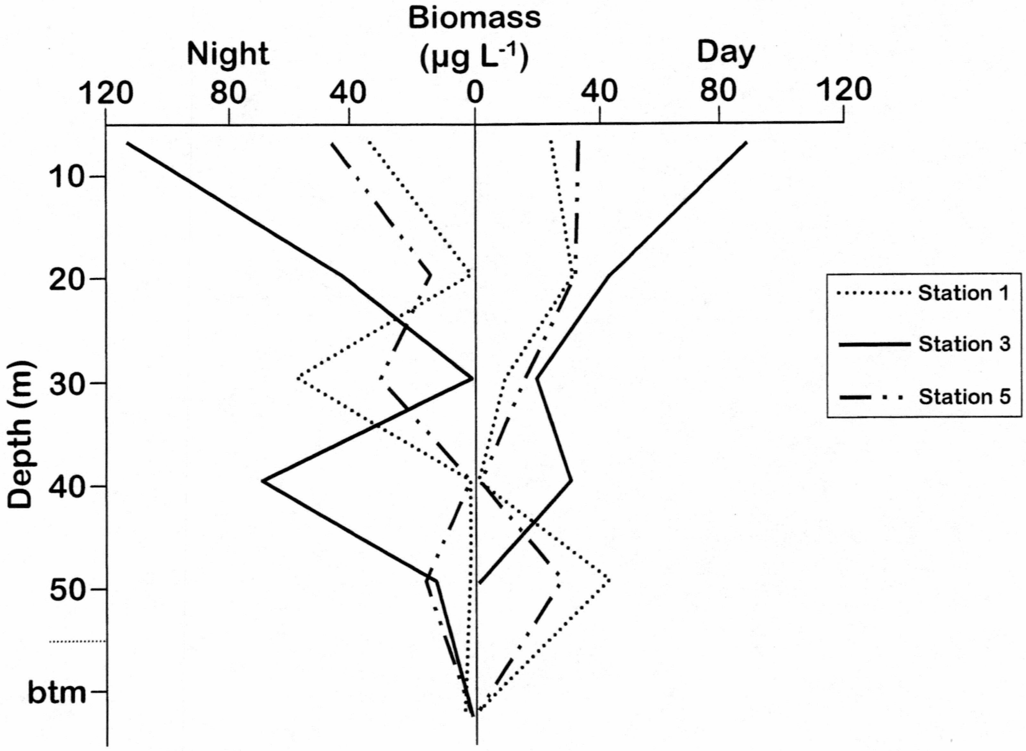

Figure 25. Zooplankton biomass versus depth, during day and night, by station. Data from June 8, 2000. Samples were not collected from stations 2 and 4 on this date.

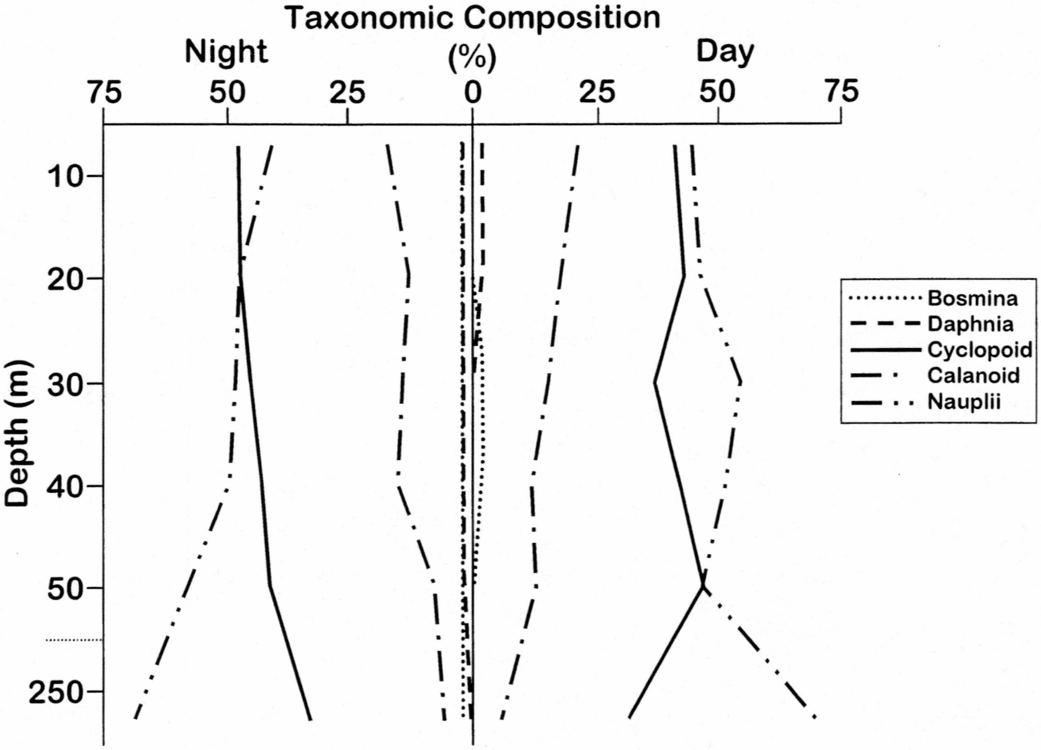

Figure 26. Zooplankton taxonomic composition versus depth, during day and night. These data are from station 5, on June 8, 2000.

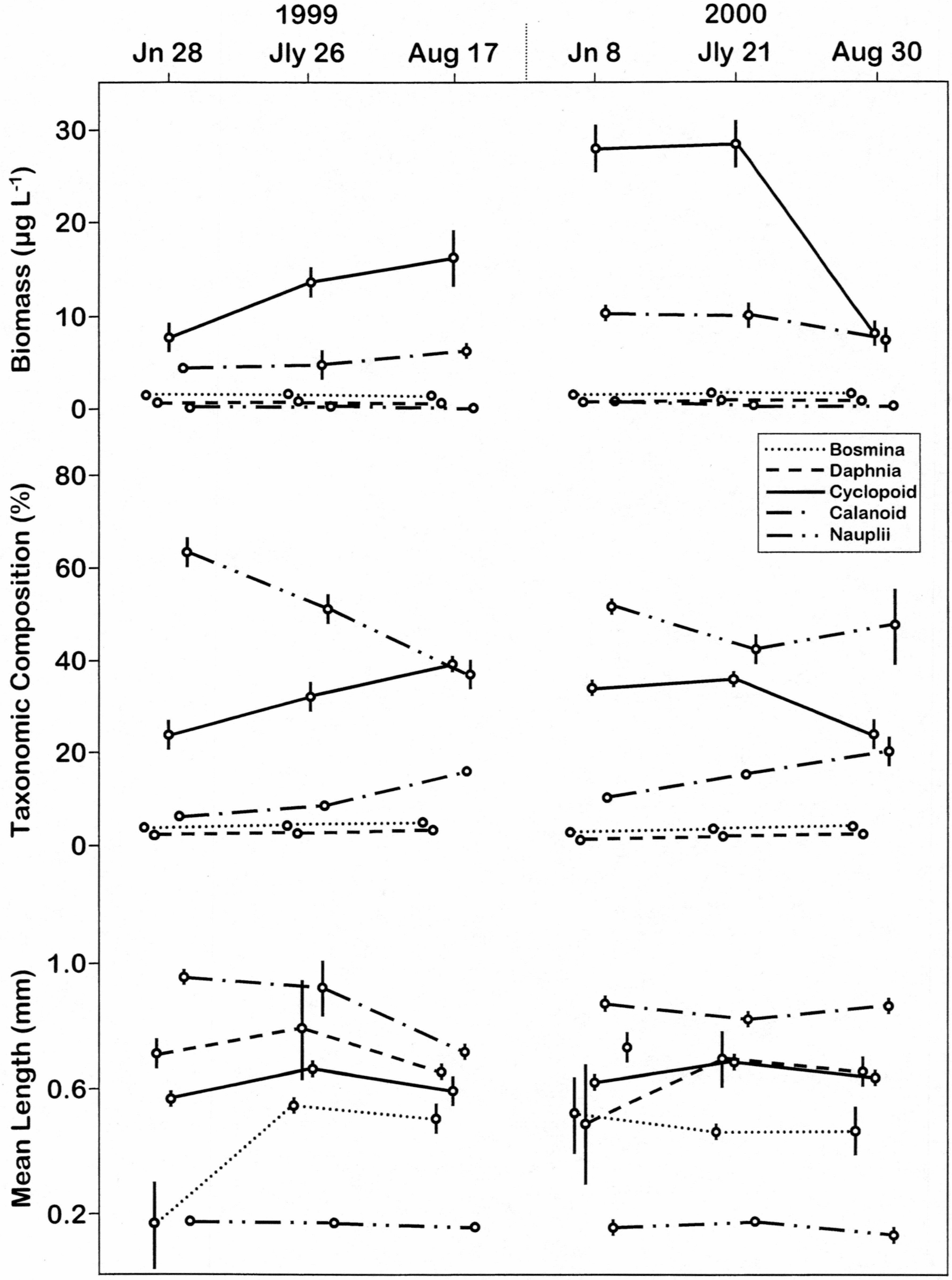

Figure 27. Zooplankton biomass, taxonomic composition, and length over time (±SE).

species may be incorrect because the keys used to identify zooplankton (Ward & Whipple, 1959; Pennak, 1978) do not include *columbianus*, a species commonly found in glacial sockeye lakes (Koenings et al., 1985; Sweetman, 2001). *Cyclops scutifer* and *Diaptomus gracilis*, were, however, the same species found by Hoag (1972) in Iliamna Lake. Unfortunately, species vouchers were accidentally destroyed before a reevaluation could be made. The rest of the taxonomic data was gathered using the ZIP, in which some *Bosmina* and *Daphnia* were also found, along with six *Holopedium* and one *Ceriodaphnia*. The zooplankton in the ZIP were not identified to species, but the *Bosmina* may have been *longirostris*, since it is the predominant cladoceran in the 23 Alaskan sockeye lakes studied by Sweetman (2001).

Length-Frequency—The length of zooplankton by taxon did not show significant variation with station, season, or year (Figure 28). *Daphnia* and calanoid copepods were the largest zooplankton measured. Their lengths ranged maximally from 0.4-1.1 and 0.7-1.1 mm, respectively. Cyclopoid copepods and *Bosmina* were smaller at 0.5-0.8 and 0.3-0.7 mm, respectively. Nauplii ranged in length from 0.15-0.23 mm.

For every sample, OPC data rendered a length-frequency plot best described as a normal curve, skewed to the right. For simplicity, and because outliers were large in size, modal length was used to describe the distribution. Equivalent Spherical Diameter (ESD) was not converted to length because OPC technology is new, and the methodologies have not matured. However, the ESD's presented here are equivalent to zooplankton lengths with an error of ± 10%. ESD and actual length equate in this case because nearly all zooplankton in Lake Clark are copepods (Figures 26 & 27), and Hopcroft (2002) found that OPC measuring error is cancelled out by copepod morphology.

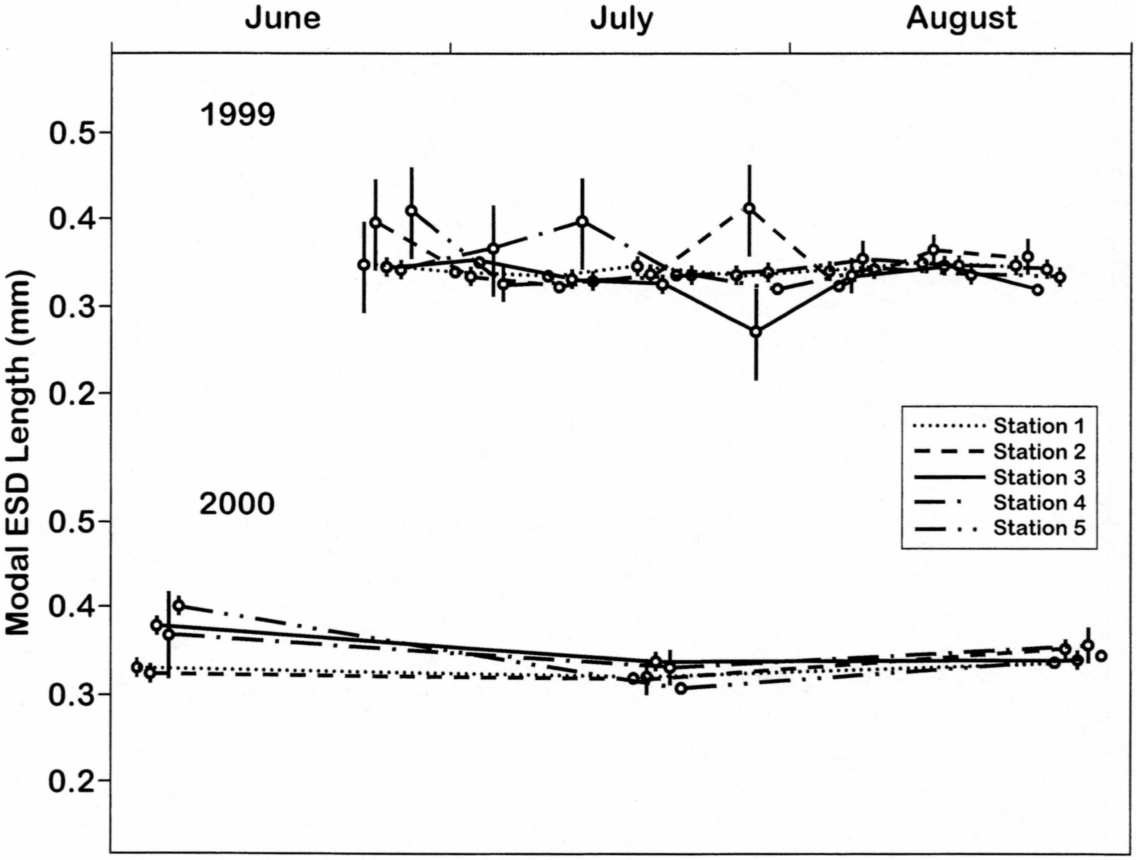

Figure 28. Zooplankton modal length at each station, for 1999 and 2000 (±SE). Data are from 50 m hauls, integrated through the water column. (ESD = Equivalent Spherical Diameter)

DISCUSSION

Limnology

Temperature—Based on the data collected in this study, Lake Clark appears dimictic, with weak summer stratification, a deep epilimnion, and no true thermocline (Figures 4 & 5). The duration of the weak summer stratification was brief; it was established by June in both 1999 and 2000 and lasted for only six weeks in the inlet basin and 16 weeks in the outlet basin (Figures 6 & 7). In 1999 temperature maxima took one month longer to develop at station 1 than at station 5, creating a longitudinal temperature gradient. However, in 2000 the pattern was reversed with temperatures at station 1 peaking two weeks before station 5. As a result of these longitudinal temperature gradients there was spatial variation in thermal profiles between stations during the summer months (Figures 8-11). Summer cooling was observed in July of both years. The lake was inversely stratified for five months in the winter of 1999-2000 and was ice-covered for four months between January and April.

The thermal regime of Lake Clark is the result of a combination of factors. The lake is at high latitude, is subject to a subarctic inland climate, has powerful tributary input, and lies in a long, narrow, and deep valley that experiences frequent and often severe storms (Western Regional Climate Center/RAWS; personal observations). Tributary discharges to the lake are significant (Table 1) and likely contribute to summer warming. In addition, tributary inputs arrive at different densities due to fluctuations in both temperature and sediment load (Table 1). Therefore, even warm glacial tributaries may have high densities due to tremendous sediment load and may, upon discharge to the lake, dive to water of equal density and in the process cause mixing at depth and weakening of stratification. As a consequence of these diverse tributary inputs, the lake's bottom topography, and frequent storms, internal water movements are likely to be powerful and complex. While collecting lake profiles instruments were often pulled strongly in different directions at different depths, presumably by in-lake currents.

Comparing results in this study to those of Edmundson and Mazumder (2002), where 60 Alaskan lakes were summarized, the 120-day growing season and the maximum surface temperature of 12°C (averaged over all stations) are to be expected given the latitude of Lake Clark. Comparing the fetch and mixing depth of Lake Clark to the same study renders a predicted mixing depth of 78 m, which is considerably deeper than the actual mixing depth of 30 m. Due to Lake Clark's long fetch, considerable extrapolation of Edmundson and Mazumders' data set was required for this prediction, However, the comparison partially explains the great depth of the thermocline in Lake Clark and suggests the fetch of the lake is broken up by the narrows at station 2, where islands are in the path of wave propagation.

Oxygen, pH, and Conductivity—Dissolved oxygen levels in the epilimnion were usually close to saturation, or were mildly supersaturated, throughout the study (Figures 12-15). During 1999 and June 2000, oxygen concentrations in metalimnetic and hypolimnetic waters were lower, but still close to saturation. Surprisingly, in July and August 2000, oxygen levels were well above saturation over a broad depth range spanning the metalimnion and upper hypolimnion. The detailed shape of oxygen profiles varied between stations, and no one area of the lake had consistently higher oxygen levels.

Primary production may explain the supersaturation of oxygen in the epilimnion. However, the pronounced supersaturation of oxygen in deeper water during July and August of 2000 cannot be explained by photosynthetic action because these peaks were well below the compensation depth. I do not have a plausible explanation for this measurement, and instrument error was unlikely since a calibration was performed immediately preceding each sampling set in 2000.

The pH values were typically slightly above neutral in the epilimnion and close to neutral at greater depths (Figure 16). This pattern may best be explained by the photosynthetic depletion of dissolved CO_2 in the euphotic zone, since even though algal biomass is low, alkalinities are also low (Deschu, 2000). This may allow moderate photosynthetic rates to raise pH slightly by reducing the concentration of carbonic acid.

The low and stable conductivity of Lake Clark indicates a minimal presence of dissolved ions and their associated nutrients, especially since pH was nearly neutral

(Figure 16). Redox potential was consistently positive down to the bottom sediments, indicating full oxidation of the water column and benthos. Since the sediment-water interface is fully oxygenated, phosphorus in the sediments will be insoluble and thus not recycled.

Results for oxygen, conductivity, and pH in the epilimnetic waters were generally similar to those of Donaldson (1967), Burgner et al. (1969), Dale & Stottlemyer (1986), and Chamberlain (1989), giving no evidence of change in these limnological variables over the last 40 years. However, in all four studies no measurements were taken from depth, and with the exception of Chamberlain (1989) there was little replication.

Light and Turbidity—A strong turbidity gradient, matched inversely by a strong light gradient, was seen along the length of the lake in both years (Figures 17-20). The turbidity gradient, high at the inlet end (station 5), developed quickly in early July and remained present throughout the summer, even though absolute turbidities decreased after July. Light levels were reduced accordingly, and in a non-linear fashion, with small increases in turbidity causing large reductions in transparency and penetration. Because of this non-linear light response, the outlet basin behaved as if it were a separate lake in terms of light penetration.

Turbidity in the form of inorganic suspended solids drives the light regime in Lake Clark because few organics are present in the water column, as evidenced by low organic suspended solids (Figures 19 & 20) and the agreement of light scatter and light absorption (Figures 17 & 18). The turbidity gradient exists because nearly all inorganic particulates are delivered to the inlet end of the lake by the three glacial tributaries (Table 1). Since the Tlikakila River is by far the largest of the three, accounting for 14-62% of Lake Clark's water budget (Brabets, 2002), the river's suspended sediment load largely determines the light regime in the lake. At the opposite end of the lake, light penetration was unperturbed until August because it took a month for the turbidity plume to travel down the lake, and glacial flour likely settles out at the face of the shallow sill at station 2. The light gradient changed in a non-linear fashion along the lake because only small increases in turbidity are needed to greatly reduce light penetration (Edmundson, J.

A. & Koenings, 1986).

Comparing turbidity and the 1% light level, Lloyd et al. (1987) found the following relationship ($r^2 = 0.85$) for 14 Alaskan lakes:

$$\log_{10} Z_{0.01} = 1.147 - 0.603 \log_{10} T,$$
where $Z_{0.01}$ = 1% light depth (m),
and T = turbidity (NTU).

By pairing values of turbidity and compensation depth for the five stations, it is evident that Lake Clark adheres closely to the above relationship and therefore is similar to many other Alaskan lakes in this regard. This similarity suggests that as a consequence of its great length, Lake Clark simultaneously exhibits the light and turbidity characteristics of several different lakes.

Phytoplankton and Nutrients—Algal biomass was generally higher at stations 1 and 2 than in the inlet basins, and was higher in the middle of the summer (Figures 21 & 22). Nutrient concentrations were consistently low, and the analytical method used showed no significant longitudinal gradient (Table 2).

The combination of static nutrient concentrations, a possible chlorophyll-*a* gradient, and a strong turbidity gradient raises the possibility that productivity is nutrient-limited at the clear end and light-limited at the turbid end. Chamberlain (1989) gives evidence of this in his nutrient enrichment experiments, where he found a positive productivity response to both nitrogen and phosphorus before the annual turbidity plume encroached, and a far less positive response during times of high turbidity.

This study confirms that Lake Clark is oligotrophic since chlorophyll-*a* concentrations were well below 4 $\mu g\ L^{-1}$ (Welch, 1980), and total phosphorus was less than 10 $\mu g\ L^{-1}$ (Vollenweider, 1968). Although nutrient ratios could not be calculated from data collected in this study, Deschu's (2000) site visit gives TN/TP ratios of 5 to 70, with an average of 33. TN/TP ratios of <13 indicate nitrogen limitation, and >21 indicate phosphorus limitation (Smith, 1979). Lake Clark bridges Smith's dichotomy, suggesting it may be limited by either nutrient during times of low turbidity.

Chlorophyll-*a* concentrations in Lake Clark were lower than expected when compared to those of north temperate lakes with equivalent phosphorus availability (Vollenweider, 1976). This holds true even when comparing Lake Clark to other Alaskan clear-water lakes (Lloyd et al., 1987). However, when comparing Lake Clark with other glacially turbid Alaskan lakes, phosphorus availability correlates well with the predicted average chlorophyll-*a* concentrations (Lloyd et al., 1987). Even though algal standing crop in Lake Clark appears low, it is similar to the biomass levels seen in other Alaskan lakes of similar glacial input.

Zooplankton

Abundance, Distribution, and Biomass—Stations 3, 4, and 5 had consistently higher densities of zooplankton than station 1 in the outlet basin (Figures 23 & 24). Nearly all zooplankton were found in the top 20 m of the water column, and the majority were in the top 10 m. Hauls from 50 m show no density differences spatially or temporally (Figure 24). Zooplankton densities were higher in late June and July than they were in early June or August. No significant vertical migration of zooplankton was detected regardless of seasonal light shifts caused by high latitude or turbidity. Patterns of biomass distribution mirrored those of density (Figures 25 & 27).

Zooplankton densities may be high in the inlet and central basins because although algal biomass is similar, predation pressure is lower because juvenile sockeye are visual predators and the water is turbid. Edmundson (pers. comm., 2002) found a similar situation in Skilak Lake, in which copepods were most abundant at the turbid end of the lake, where Secchi depths were reduced to 0.5 m. Zooplankton undoubtedly concentrated in the surface waters to feed on algae in the euphotic zone. The decrease in zooplankton densities seen in August may be due to the cumulative effect of sockeye predation over the summer (Foerster, 1968). However, the absence of vertical migration suggests predation pressure was low.

The only other large data set on zooplankton in Lake Clark was compiled by

Schlenger (1996). Unfortunately, our results are not directly comparable because he used horizontal tows to collect samples while I used vertical hauls. Perhaps as a consequence, Schlenger's sample variances were high and therefore did not demonstrate the spatial variations in abundance that I found in this study. Comparing the densities of zooplankton in Lake Clark to those in the lakes summarized by Lloyd et al. (1987) indicates the relationship between compensation point and zooplankton density for Lake Clark is similar to other semi-glacial lakes.

Taxonomic Composition—Copepods accounted for nearly all the zooplankton in the lake, with cladocerans making up the balance (Figures 26 & 27). Taxonomic composition changed little with depth, time of day, season, or year.

Cyclops and *Diaptomus* dominate the zooplankton assemblage of Lake Clark most likely because limnetic cladocerans have been excluded by a trophic "squeeze." Limnetic cladocerans are indiscriminant filter feeders whose digestive tracts become blocked by glacial silt (Edmundson, J. M. & Koenings, 1986) and can therefore be excluded from glacially influenced lakes (Koenings et al., 1985; Koenings et al., 1990). In addition, cladocerans are selectively preyed upon by sockeye juveniles, even when copepods are abundant (Goodlad et al., 1974; Vinyard et al., 1982; Kyle et al., 1988; Schlenger, 1996), suggesting the limited numbers of *Bosmina* in Lake Clark may be caused by the sockeye themselves (Koenings & Kyle, 1997).

The taxonomic compositions reported in this study are nearly identical to those found in Lake Clark by Schlenger (1996). However, in 23 other Alaska sockeye salmon lakes (Sweetman, 2001), and in Iliamna Lake (Hoag, 1972), the ratio of *Bosmina* to *Cyclops* was higher than that found in Lake Clark, probably because of glacial exclusion of *Bosmina.* The low ratio of *Bosmina* to copepods may limit the potential for sockeye productivity in Lake Clark (Koenings et al., 1985).

Length-Frequency—Zooplankton lengths varied little throughout the study (Figure 28). This lack of variation suggests either predation pressure is low, or size-selective predation pressure is constant.

Compared to zooplankton in the 23 Alaskan sockeye lakes summarized by

Sweetman (2001), in Lake Clark the *Bosmina* were large (> 0.4 mm), the *Daphnia* were also large (> 0.65 mm), and the *Cyclops* were of average size (~ 0.6 mm). Sweetman found that *Bosmina* were large in lakes where *Cyclops* densities were high. This may be a consequence of natural selection favoring large *Bosmina*, because they are less vulnerable to predation by *Cyclops*.

CONCLUSIONS

Turbidity caused by glacial flour has significant impacts on aquatic production beginning with effects on temperature regimes, light profiles, and nutrient inputs (Koenings et al., 1986; Lloyd et al., 1987; Edmundson & Mazumder, 2002). These impacts ripple up the food chain to reduce zooplankton production (Koenings et al., 1986). The elongated shape of Lake Clark, combined with large glacial tributaries at the inlet end, results in a pronounced turbidity gradient down the length of the lake during the summer. As a consequence of this gradient algal productivity is likely to be light-limited at the inlet end and nutrient limited at the outlet end.

Zooplankton spatial distribution is likely a combination of algal availability and predation pressure. Zooplankton densities may have been highest in the central basin because moderate levels of turbidity allowed for high productivity and low predation risk. Higher algal productivities in the central basin were not reflected by chlorophyll-*a* values, but that may be because zooplankton grazing rates were correspondingly high. A similar situation was described by Power (1984), in which algal productivity was different in two pools, but algal biomass was the same in both pools due to catfish grazing rates corresponding to algal productivity rates.

The warming of the lake in summer is likely caused more by tributary inputs than direct solar heating. The deep, weak thermoclines and unusual longitudinal temperature patterns can both be attributed to strong winds acting on the tremendous fetch of the lake in conjunction with tributaries arriving at different temperatures and with different sediment loads. Photosynthesis likely explains the high oxygen levels in the surface waters, but supersaturation of hypolimnetic waters is probably not instrument error, and so remains a mystery.

FUTURE STUDY

The following are suggestions for monitoring and future research:

- Set GPS-fixed sampling points in the center of the deepest portion of each of Lake Clark's three main basins.
- Take depth profiles for temperature at each station at the beginning, middle, and end of the growing season to check the strength of stratification.
- Measure Secchi depth and turbidity concurrently with temperature. Use standard procedures (Carlson, 1995), and apply the rule of 3*(Secchi depth) = compensation depth, since that seems to be most appropriate for Lake Clark. Sample for turbidity at the surface or over the top 20 m because Secchi depth measurements lose resolution at high turbidities. A decrease in Secchi depth or an increase in turbidity that persists for more than five years could signal abnormally high levels of suspended sediments.
- Collect chlorophyll-*a* measurements yearly or concurrently with temperature readings. A persistent decrease in algal biomass could signal oligotrophication through reduced light or nutrient availability due to increased suspended sediment loading by glacial tributaries. Integrated samples taken through a depth of 50 m would give results directly comparable to this study, but discrete depth samples focused on the top 20 m would suffice.
- Sample zooplankton monthly with vertical hauls from 10 m and 20 m at each station during the summer months. Dry and weigh samples to estimate biomass. If the average biomass consistently increases or decreases for more than five years, launch a more intensive study.
- Investigate the link between in-lake circulation and inputs of heat, sediment, and nutrients. Describing this link would create a powerful model of productivity limitation and mixing in Lake Clark, and could explain supersaturation of oxygen in the hypolimnion. Any future mixing study should consider internal seiches and metalimnetic entrainment as causes of weak stratification, and should look

for evidence of polymixus.

- Study the heat, dissolved gases, and organic and inorganic materials produced by the smaller watersheds of the Lake Clark basin. Little is known about the smaller catchments that feed Lake Clark, but they likely play a role in the biological integrity of the park ecosystem.
- Initiate a study of the major ions in Lake Clark to confirm or refute previous findings (Chamberlain, 1989) and determine if the lake is acid-sensitive and requires further monitoring.
- Undertake a comprehensive nutrient study that includes stimulation experiments to determine the nutrient limiting the productivity of Lake Clark. The nutrients in carcasses of returning adult salmon can increase productivity in oligotrophic lakes (Krokhin, 1957; Kline et al., 1997), suggesting a study of marine-derived nutrients could be fruitful. Future productivity studies should account for light limitation and use methods capable of detecting very low nutrient levels.
- Sample for heavy metals and trace elements to set a baseline for future studies of volcanism affecting Lake Clark.
- Investigate the taxonomic composition, size fraction, and biomass of primary producers in the lake to fill the existing knowledge gap between nutrients and zooplankton. Density measurements may reveal seasonal taxonomic shifts that correlate with turbidity. Future plankton studies should take discrete depth samples to determine depth distribution.
- Conduct hydroacoustic surveys in conjunction with zooplankton sampling to determine the relationship between juvenile sockeye salmon, zooplankton, and turbidity in Lake Clark. Evidence of spatial banding of sockeye and least cisco (*Coregonus sardinella*) in Lake Clark was reported by Brannian et al. (1981). These zooplanktivores may concentrate at the edge of the turbidity plume in correlation with the high zooplankton densities found in this study.

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APPENDIX A. Station locations, coordinates, and depths.

Station	Lake Section	Deg	Min	Sec		Depth (m)
1	Outlet Basin	60	4	11.7	N	100
		154	38	17.52	W	
2	Outlet Shelf	60	8	33.24	N	70
		154	28	30.48	W	
3	Central Basin	60	16	1.38	N	260
		154	14	35.4	W	
4	Inlet Shelf	60	19	2.94	N	220
		154	3	25.86	W	
5	Inlet Basin	60	20	11.16	N	180
		154	0	27.06	W	

APPENDIX B. Temperature data (°C) from Hydrolab sampling.

June 28, 1999

Depth (m) \ Station	1	2	3	4	5
1	7.50	8.37	7.11	6.11	7.82
2	7.22	7.73	7.08	5.65	7.51
3	6.99	7.50	7.01	5.13	7.51
4	6.66	7.42	7.03	5.04	6.78
5	6.63	7.36	6.99	5.04	5.96
10	6.32	6.91	5.19	4.93	5.68
20	5.11	5.36	4.11	4.36	4.61
30	4.51	5.07	3.81	4.02	4.20
40	4.35	4.08	3.77	3.92	4.09
50	4.16	3.73	3.78	3.91	4.07
70	3.95		3.73	3.82	3.97
90	3.79		3.70	3.78	3.97
110	3.76		3.68	3.73	3.99
130			3.68	3.69	4.01
150			3.71	3.63	3.97
170			3.73	3.61	4.01
190			3.72		

July 5, 1999

Depth (m) \ Station	1	2	3	4	5
1	8.30	8.33	10.38	10.49	10.40
2	7.95	8.19	9.94	10.29	10.28
3	7.68	8.18	9.55	9.80	10.22
4	7.57	7.66	9.42	8.42	10.18
5	7.57	7.03	9.28	7.66	10.17
10	7.10	6.38	8.10	6.13	8.65
20	5.58	5.37	6.48	4.29	6.42
30	4.93	4.60	4.62	4.01	4.95
40	4.53	4.00	4.04	3.90	4.26
50	4.42	3.74	3.90	3.87	3.95
70	4.06	3.71	3.83	3.80	3.79
90	3.92		3.77	3.78	3.75
110	3.83		3.73	3.73	3.67
130			3.69	3.66	3.65
150			3.67	3.64	3.71
170			3.69	3.63	4.00
190			3.67		

July 11, 1999

Depth (m) \ Station	1	2	3	4	5
1	8.39	9.34	11.89	12.30	11.70
2	8.19	9.28	11.43	11.88	11.27
3	8.07	9.26	11.13	11.11	11.22
4	7.56	9.26	10.90	10.15	11.06
5	7.30	9.22	10.81	9.75	10.86
10	6.68	9.08	9.38	8.33	8.54
20	5.19	8.37	6.76	5.51	5.74
30	4.65	7.55	5.30	4.16	4.35
40	4.34	6.38	4.56	3.92	4.06
50	4.22	5.54	4.06	3.87	4.12
70	4.06	4.20	3.87	3.77	4.05
90	3.90		3.83	3.71	4.03
110	3.89		3.80	3.68	4.00
130			3.76	3.65	3.81
150			3.70	3.62	3.75
170			3.66	3.59	3.82
190			3.64	3.59	

July 19, 1999

Depth (m) \ Station	1	2	3	4	5
1	8.83	10.75	10.89	NA	NA
2	8.79	10.53	10.89	NA	NA
3	8.78	10.53	10.87	NA	NA
4	8.77	10.47	10.84	NA	NA
5	8.70	10.43	10.84	NA	NA
10	6.92	10.37	10.79	NA	NA
20	5.42	8.14	7.90	NA	NA
30	4.71	4.89	6.08	NA	NA
40	4.52	4.29	5.12	NA	NA
50	4.31	4.20	4.34	NA	NA
70	4.10		3.93	NA	NA
90	4.02		3.80	NA	NA
110			3.79	NA	NA
130			3.78	NA	NA
150			3.77	NA	NA
170			3.71	NA	NA
190			3.65		

July 26, 1999

Depth (m) \ Station	1	2	3	4	5
1	9.16	9.37	10.29	10.84	10.34
2	8.95	9.37	10.19	10.81	10.33
3	8.92	9.34	10.13	10.79	10.32
4	8.90	9.29	10.04	10.76	10.27
5	8.91	9.26	9.01	10.70	10.29
10	8.75	9.16	8.93	10.49	10.10
20	5.18	7.35	8.26	9.98	9.17
30	4.61	6.46	5.98	7.12	7.38
40	4.40	4.95	4.69	5.10	5.13
50	4.25	4.36	4.09	4.15	4.27
70	4.13		3.97	3.97	4.16
90	4.05		3.87	3.83	4.13
110	3.92		3.82	3.80	4.10
130			3.81	3.74	4.09
150			3.76	3.73	4.10
170			3.72	3.74	4.07
190			3.69		

Aug 1, 1999

Depth (m) \ Station	1	2	3	4	5
1	10.59	10.79	10.82	10.68	10.89
2	10.30	10.77	10.80	10.65	10.88
3	10.20	10.57	10.70	10.66	10.88
4	10.16	10.43	10.69	10.65	10.85
5	10.10	10.40	10.68	10.65	10.79
10	9.88	10.34	10.61	10.63	9.81
20	6.59	7.75	7.68	9.40	7.03
30	5.51	5.11	6.37	6.03	5.31
40	4.70	4.86	5.63	4.01	4.49
50	4.45	4.03	4.76	3.96	4.30
70	4.20		4.04	3.87	4.18
90	4.04		3.88	3.81	4.14
110	3.93		3.85	3.74	4.11
130			3.81	3.71	4.09
150			3.76	3.74	4.07
170			3.71	3.75	4.06
190			3.67		

APPENDIX B. (continued)

Aug 7, 1999

Depth (m) \ Station	1	2	3	4	5
1	10.58	10.61	10.32	7.53	8.64
2	10.58	10.60	10.23	7.49	8.64
3	10.58	10.61	10.17	7.28	8.53
4	10.57	10.60	10.18	7.20	8.40
5	10.57	10.60	9.96	7.19	8.09
10	10.36	10.59	9.37	6.52	7.36
20	9.32	7.37	8.34	5.67	6.15
30	6.30	4.45	6.77	5.03	5.39
40	4.95	4.01	6.20	4.51	5.09
50	4.60	3.80	4.86	4.34	4.89
70	4.20		4.29	4.13	4.55
90	4.05		4.18	3.98	4.43
110	3.91		4.09	3.95	4.24
130			4.06	3.91	4.20
150			4.02	3.88	4.45
170			3.92	3.81	4.72
190			3.88		

Aug 17, 1999

Depth (m) \ Station	1	2	3	4	5
1	NA	NA	12.44	11.57	11.93
2	NA	NA	12.15	11.49	11.62
3	NA	NA	12.04	11.30	11.05
4	NA	NA	11.76	10.92	10.68
5	NA	NA	11.16	10.70	10.60
10	NA	NA	10.26	9.80	10.33
20	NA	NA	7.89	7.81	8.51
30	NA	NA	7.36	6.42	6.84
40	NA	NA	6.13	5.79	5.84
50	NA	NA	5.47	5.09	5.37
70	NA		4.75	4.41	4.67
90	NA		4.32	4.17	4.36
110			4.13	3.98	4.20
130			3.98	3.89	4.11
150			3.90	3.86	4.04
170			3.84	3.78	4.00
190			3.76		

June 8, 2000

Depth (m) \ Station	1	2	3	4	5
1	7.50	8.37	7.11	6.11	7.82
2	7.22	7.73	7.08	5.65	7.51
3	6.99	7.50	7.01	5.13	7.51
4	6.66	7.42	7.03	5.04	6.78
5	6.63	7.36	6.99	5.04	5.96
10	6.32	6.91	5.19	4.93	5.68
20	5.11	5.36	4.11	4.36	4.61
30	4.51	5.07	3.81	4.02	4.20
40	4.35	4.08	3.77	3.92	4.09
50	4.16	3.73	3.78	3.91	4.07
70	3.95		3.73	3.82	3.97
90	3.79		3.70	3.78	3.97
110	3.76		3.68	3.73	3.99
130			3.68	3.69	4.01
150			3.71	3.63	3.97
170			3.73	3.61	4.01
190			3.72		

July 21, 2000

Depth (m) \ Station	1	2	3	4	5
1	8.30	8.33	10.38	10.49	10.40
2	7.95	8.19	9.94	10.29	10.28
3	7.68	8.18	9.55	9.80	10.22
4	7.57	7.66	9.42	8.42	10.18
5	7.57	7.03	9.28	7.66	10.17
10	7.10	6.38	8.10	6.13	8.65
20	5.58	5.37	6.48	4.29	6.42
30	4.93	4.60	4.62	4.01	4.95
40	4.53	4.00	4.04	3.90	4.26
50	4.42	3.74	3.90	3.87	3.95
70	4.06	3.71	3.83	3.80	3.79
90	3.92		3.77	3.78	3.75
110	3.83		3.73	3.73	3.67
130			3.69	3.66	3.65
150			3.67	3.64	3.71
170			3.69	3.63	4.00
190			3.67		

August 30, 2000

Depth (m) \ Station	1	2	3	4	5
1	8.39	9.34	11.89	12.30	11.70
2	8.19	9.28	11.43	11.88	11.27
3	8.07	9.26	11.13	11.11	11.22
4	7.56	9.26	10.90	10.15	11.06
5	7.30	9.22	10.81	9.75	10.86
10	6.68	9.08	9.38	8.33	8.54
20	5.19	8.37	6.76	5.51	5.74
30	4.65	7.55	5.30	4.16	4.35
40	4.34	6.38	4.56	3.92	4.06
50	4.22	5.54	4.06	3.87	4.12
70	4.06	4.20	3.87	3.77	4.05
90	3.90		3.83	3.71	4.03
110	3.89		3.80	3.68	4.00
130			3.76	3.65	3.81
150			3.70	3.62	3.75
170			3.66	3.59	3.82
190			3.64	3.59	

APPENDIX C. Secchi depth, compensation point, light attenuation and Forel color.

Secchi Depth (m)

	1999								2000		
Station	June 28	July 5	July 11	July 19	July 26	Aug 1	Aug 7	Aug 17	June 8	July 21	Aug 30
1	8.6	8.3	9	6.4	7.5	4.6	2	4.2	4.6	2	4.2
2	6.6	8	2.6	3.1	2.1	1.4	1.4	2.5	1.4	1.4	2.5
3	6.9	1.8	1.7	0.6	1.4	1	1.3	1.8	1	1.3	1.8
4	6	1.1	0.5	1	1.1	1	0.9	1.4	1	0.9	1.4
5	4.5	2.6	0.3	1	1	1	0.9	1.6	1	0.9	1.6

Compensation Point (depth of 1% light) (m)

	1999								2000		
Station	June 28	July 5	July 11	July 19	July 26	Aug 1	Aug 7	Aug 17	June 8	July 21	Aug 30
1	23	21	24	24	22	16	12	13	20	18	13
2	16	17	11	14	11	7	10	8	14	8	10
3	16	8	9	7	8	6	8	9	16	8	9
4	18	9	4	5.5	7	7	7	7	21	5	8
5	13	10	3	5	7	7	7	7	23	5	8

Coefficient of Light Attenuation (Kd)

	1999								2000		
Station	June 28	July 5	July 11	July 19	July 26	Aug 1	Aug 7	Aug 17	June 8	July 21	Aug 30
1	0.09	0.09	0.08	0.09	0.09	0.13	0.17	0.16	0.10	0.11	0.16
2	0.12	0.12	0.20	0.15	0.20	0.28	0.22	0.25	0.15	0.25	0.21
3	0.13	0.25	0.24	0.33	0.25	0.33	0.27	0.24	0.13	0.25	0.22
4	0.10	0.22	0.59	0.44	0.29	0.32	0.33	0.29	0.10	0.45	0.24
5	0.15	0.21	0.72	0.53	0.34	0.30	0.30	0.29	0.11	0.39	0.26

Forel-Ule Color

	1999								2000		
Station	June 28	July 5	July 11	July 19	July 26	Aug 1	Aug 7	Aug 17	June 8	July 21	Aug 30
1	F7	F7	F7	F7	F7	F11	F9	F11	F10	F6	F11
2	F10	F6	F5	F9	F8	F11	F9	F10	F9	F10	F9
3	F10	F10	F6	F9	F5	F9	F11	F11	F9	F11	F8
4	F9	F7	F4	F8	F9	F7	F6	F10	F7	F7	F10
5	F9	F10	F5	F9	F11	F8	F9	F10	F7	F7	F11

APPENDIX D. Turbidity, suspended solids, chlorophyll-*a*, and true color.

Station	Date	Turbidity (NTU's)		Inorg. Sus. Solids (µg/L)		Org. Sus. Solids (µg/L)		Chlorophyll-*a* (µg/L)		True Color (platinum-cobalt)	
		Average	Std Dev.	Average	Std Dev.	Average	Std Dev.	Average	Std Dev.	Average	Std Dev.
1	June 28, 1999	1.2	0.26	0.58	0.10	1.43	0.59	0.96	0.052	13.7	4.5
1	July 5, 1999	0.9	0.04	0.05	0.13	1.53	0.75	0.93	0.034	0.0	0.0
1	July 11, 1999	0.7	0.08	0.07	0.12	2.93	0.59	0.93	0.047	3.7	1.2
1	July 19, 1999	1.0	0.14	0.63	0.19	1.10	0.26	0.84	0.034	14.0	3.5
1	July 26, 1999	1.0	0.18	0.43	0.41	1.70	0.82	1.08	0.067	3.0	2.0
1	Aug 1, 1999	1.0	0.12	0.68	0.24	2.13	0.15	1.40	0.065	0.0	0.0
1	Aug 7, 1999	2.0	0.05	1.17	0.39	2.00	0.96	1.11	0.013	13.7	4.0
1	Aug 17, 1999	2.1	0.20	1.32	0.03	2.00	0.26	0.78	0.052	11.3	0.6
2	June 28, 1999	1.5	0.15	0.40	0.05	1.03	0.06	0.74	0.022	0.0	0.0
2	July 5, 1999	1.0	0.14	0.33	0.15	2.57	0.55	0.94	0.022	1.3	1.5
2	July 11, 1999	2.1	0.25	0.60	0.58	2.37	0.21	1.35	0.034	3.7	1.2
2	July 19, 1999	1.7	0.18	0.82	0.29	0.83	0.35	0.93	0.034	9.7	1.2
2	July 26, 1999	3.7	0.62	0.87	0.37	0.73	0.15	0.80	0.013	4.3	2.3
2	Aug 1, 1999	3.5	0.05	1.48	0.10	2.17	0.67	0.70	0.013	2.0	1.7
2	Aug 7, 1999	2.9	0.06	1.55	0.33	1.27	0.25	0.57	0.056	16.0	0.0
2	Aug 17, 1999	4.6	0.17	2.62	0.29	1.83	0.87	0.84	0.013	13.0	3.6
3	June 28, 1999	2.1	0.78	0.88	0.20	2.57	0.38	0.57	0.068	14.0	2.0
3	July 5, 1999	2.5	0.07	0.67	0.14	1.23	0.15	0.90	0.090	0.0	0.0
3	July 11, 1999	4.6	0.09	2.37	0.55	2.00	0.40	0.90	0.013	15.3	2.3
3	July 19, 1999	5.5	0.12	0.40	0.13	1.73	0.15	0.82	0.034	16.3	1.5
3	July 26, 1999	4.3	0.14	2.25	0.69	1.30	0.40	0.79	0.047	12.7	2.9
3	Aug 1, 1999	6.7	0.27	3.58	0.21	1.43	0.47	0.70	0.013	18.7	3.1
3	Aug 7, 1999	7.7	0.15	3.90	0.26	2.60	0.26	0.60	0.022	7.3	4.0
3	Aug 17, 1999	7.5	0.70	4.26	0.30	2.07	0.81	0.75	0.052	6.3	1.2
4	June 28, 1999	1.3	0.14	0.72	0.13	1.13	0.47	0.62	0.056	0.0	0.0
4	July 5, 1999	2.0	0.18	0.53	0.20	1.77	0.32	0.75	0.047	0.0	0.0
4	July 11, 1999	6.5	0.21	2.68	0.43	1.77	0.75	0.73	0.013	18.7	1.2
4	July 19, 1999	5.4	0.17	3.03	0.15	1.37	0.21	0.75	0.072	20.3	2.5
4	July 26, 1999	8.8	0.11	3.77	0.45	1.93	1.10	0.81	0.034	19.3	1.2
4	Aug 1, 1999	8.7	0.29	3.72	0.25	2.20	0.75	0.71	0.013	20.0	2.0
4	Aug 7, 1999	5.9	0.25	3.15	0.22	1.80	0.36	0.46	0.013	4.0	3.6
4	Aug 17, 1999	6.4	0.15	2.87	0.25	1.97	1.71	0.69	0.022	3.7	2.3
5	June 28, 1999	1.7	0.03	1.05	0.13	1.07	0.06	0.71	0.072	7.7	1.2
5	July 5, 1999	3.0	0.16	1.17	0.08	1.90	0.17	0.86	0.056	0.0	0.0
5	July 11, 1999	10.8	0.15	5.00	0.15	3.10	1.06	0.69	0.026	29.0	3.5
5	July 19, 1999	9.6	0.23	4.42	0.31	2.22	0.86	0.74	0.019	24.2	2.3
5	July 26, 1999	8.3	0.31	3.83	0.46	1.33	0.67	0.79	0.013	19.3	1.2
5	Aug 1, 1999	9.5	0.11	4.65	0.57	1.60	0.62	0.64	0.034	16.0	0.0
5	Aug 7, 1999	6.0	0.83	3.18	0.18	1.90	0.20	0.53	0.013	3.3	2.9
5	Aug 17, 1999	8.6	0.04	4.38	0.58	2.00	0.20	0.82	0.034	7.7	1.2
1	June 8, 2000	0.8	0.04	0.30	0.10	0.70	0.10	0.99	0.018	8.3	3.1
1	July 21, 2000	1.0	0.08	0.47	0.13	1.53	0.31	1.38	0.047	12.3	1.5
1	Aug 30, 2000	2.0	0.10	1.20	0.12	3.07	0.32	0.85	0.061	0.0	0.0
2	June 8, 2000	1.3	0.12	0.67	0.05	1.07	0.12	0.93	0.047	7.7	3.1
2	July 21, 2000	4.1	0.18	2.17	0.15	1.13	0.31	0.85	0.030	18.7	1.2
2	Aug 30, 2000	2.3	0.17	1.33	0.58	2.37	0.35	0.63	0.047	0.0	0.0
3	June 8, 2000	1.3	0.03	0.60	0.20	0.93	0.15	0.68	0.063	9.7	2.3
3	July 21, 2000	6.6	0.34	3.17	0.14	1.43	0.23	0.67	0.053	19.3	1.2
3	Aug 30, 2000	4.7	0.17	2.37	0.55	2.30	0.66	0.53	0.018	3.0	3.5
4	June 8, 2000	1.4	0.26	0.73	0.13	1.57	0.49	0.68	0.047	0.0	0.0
4	July 21, 2000	10.2	0.34	5.80	0.20	1.83	0.23	0.61	0.030	21.7	1.5
4	Aug 30, 2000	6.9	0.23	3.30	0.43	3.03	0.67	0.67	0.030	3.7	4.6
5	June 8, 2000	1.2	0.06	0.60	0.13	0.67	0.40	0.68	0.018	0.0	0.0
5	July 21, 2000	9.3	0.11	5.67	0.08	1.83	0.76	0.65	0.063	20.3	2.1
5	Aug 30, 2000	6.5	0.26	3.73	0.15	1.70	0.52	0.65	0.018	2.0	2.6

APPENDIX E. Nutrients. (Samples taken July 22, 2000; units are mg L^{-1} as N or P.)

Constituent	Reported Values by Station					Detection
	1	2	3	4	5	Limit
nitrogen, ammonia dissolved	0.008	0.006	< 0.002	< 0.002	0.005	0.002
nitrogen, ammonia + organic nitrogen dissolved	~ 0.10	~ 0.10	~ 0.10	< 0.10	< 0.10	0.10
nitrogen, ammonia + organic nitrogen total	< 0.10	0.40	~ 0.08	< 0.10	< 0.10	0.10
nitrogen, nitrite + nitrate dissolved	0.183	0.180	0.183	0.186	0.190	0.005
nitrogen, nitrite dissolved	0.001	0.001	0.001	0.001	0.001	0.001
phosphorus dissolved	< 0.006	< 0.006	< 0.006	< 0.006	< 0.006	0.006
phosphorus, orthophosphate dissolved	0.001	0.002	0.002	0.002	0.002	0.001
phophorus total	< 0.008	~ 0.005	~ 0.005	0.009	0.008	0.008

APPENDIX F. Data on compact disc.

The following files contain the data generated during this study. The data are saved in tab-delimited text files ("*.txt"). All the files are on the compact disc located in a sleeve on the inside back cover. If you do not have the CD, it is available in the Rasmuson Library, at the University of Alaska Fairbanks, in Fairbanks, Alaska.

Wilkens 2002 Lake Clark Temperature Logger Data.txt

Temperature (stationary HOBOtemp probes)

Wilkens 2002 Lake Clark Water Quality Data.txt

Temperature (Hydrolab profiles)

Dissolved Oxygen (concentration & percent)

Conductivity

Redox Potential

pH

Secchi Depth

Compensation Point (1% light level)

Light Attenuation (K_d)

Forel-Ule Color

True Color

Nutrients

Turbidity

Inorganic Suspended Solids

Organic Suspended Solids

Chlorophyll-*a* concentration

Wilkens 2002 Lake Clark Zooplankton Data.txt

Optical Plankton Counter Length and Density

Zooplankton Imaging Process Length, Biomass, Tax. Comp., and Weight